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## Preliminary Observations Regarding LDV Scans of Panels Excited by Broadband Actuators at the U.S. Capitol

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<b>13. SUPPLEMENTARY NOTES</b>					
<b>14. ABSTRACT</b>  Experiments were conducted on frescos and wall paintings at the U.S. Capitol Building in order to determine the effectiveness of an electromagnetic shaker-based approach of evaluating the condition of the substructure. A scanning laser Doppler vibrometer (LDV) was used to measure the vibratory response of the work of art subjected to the shaker excitation. This report contains a representative sample of the data obtained on two panels as well as a short synopsis of several observations and conclusions made regarding this data. Processed velocity data, in conjunction with data derived from traditional methodologies, indicate that the shaker-based LDV approach is an effective method for the efficient mapping of areas of structural deficiencies in need of amelioration by a conservation engineer.					
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# **PRELIMINARY OBSERVATIONS REGARDING LDV SCANS OF PANELS EXCITED BY BROADBAND ACTUATORS AT THE US CAPITOL**

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## **INTRODUCTION**

The United States Capitol has large expanses of important fine art and decorative paintings executed directly on the original lime plaster. These paintings, which are invaluable for historical and aesthetic reasons, cannot be separated from the plaster without extreme risk. This has necessitated that the integrity of the supporting structures be evaluated in-situ so that degradations underlying the artwork can be located and repaired. In support of an on-going restoration and preservation program in the building, the authors were invited to demonstrate and evaluate one of their new concepts for non-destructive evaluation of the integrity of such structures on several panels in the Brumidi Corridor in the Senate Wing of the United States Capitol.

The following represents a short synopsis of several observations we have made regarding measurements made at the U.S. Capitol using a scanning LDV to map normal velocity of two panels when each was excited at one point by a broadband force actuator. The panels are identified as 6W1S (panel 1) and 6S1W (panel 2), the latter being what is called a pilaster. Regarding panel integrity, Panel 1 is



Figure 1 – “Pineapple” Panel

characterized as simple in the sense that tapping tests indicate defect areas that involve less than 10% of the total panel area. Panel 2, on the other hand, is more complex in that at least 50% of the panel area appears to have some defects. The scan density was every three cm for panel 1 and every one cm for panel 2.

## PANEL 1

We first discuss the measurements taken on Panel 1 (see Fig. 1). Simple sequential observations (see Figs. 2a - 2g and Figs. 3a - 3f) of the velocity scans (phase and amplitude) at each three Hertz increment indicate that we have obtained meaningful data on panel 1 over the band from about 80Hz to 1KHz. From 80Hz to about 400 Hz we can observe what appears to be simple wave propagation from the lower left corner where the actuator is located up toward the upper right hand corner. This seems especially clear from the phase plots. The wave speed is very crudely estimated to be about 700 m/sec over this lower band, suggesting shear wave propagation in the plaster. Beginning just below 400 Hz one can see even higher motions over a smaller patch size (about 18cm by 26 cm) near the right edge just above the scanned panel center. It appears strongest at about 460 Hz and seems to fade in and out with something like a 25-40 Hz period. At about 670 Hz, the motion over this patch breaks into a two-lobe mode pattern. Both the extent and location of this mobile patch coincides with a defect area discovered earlier in the tap test data. We should point out, however, that the same tap test data seems to indicate another defect area on the left, a location where we do not see any obvious localized high levels of motion in the LDV maps in this frequency band.

An attempt was made to combine the individual narrow-band scans into a broadband map. We did this by forming the sum over the frequency bands of the properly normalized quantity  $|VV^*|$  at each spatial point. The resulting maps are shown in Figs. 4a - 4c for the full band and two partial bands, respectively. In addition to the dominant mobile patch in the upper right previously discussed, there appears to be additional larger areas with levels lower by some 30dB. As can be seen in Figs. 4b and 4c, these seem to be dependent on frequency. At this point, we are not certain whether these broader features are actually related to increased mobility of the structure or a signal to noise related artifact.

## PANEL 2

Panel 2 (Fig. 5) is on what is known as a pilaster, a segment of the wall that protrudes rectangularly from the wall. Observation of the velocity phase plots (see Figs. 6a - 6l) indicates that we have obtained meaningful data on this panel 2 from about 500Hz to 6KHz. Generally, what appeared as simple wave motion (shear) in panel 1 can be seen again in the panel 2 data up to about 1KHz. However, the higher frequency panel 2 data which is available beyond 1 KHz begins to look more modal in character. However, the spatial mode structure still seems to be related to shear wavenumbers. As in panel 1, at the lower frequencies (below about 1KHz) a local patch with high mobility is readily seen against the long wavelength wave motion. However, as frequency is increased, it becomes more difficult to notice such regions because of the modal-like structure of the base panel motion. However, at some frequencies it is still possible to do so when the local patch motion reaches high enough velocity levels. This is the case, for example, at around 800Hz and 980Hz where a high mobility patch can be observed just in from the left panel edge at the vertical midline; between about 860Hz and 930Hz where both this patch and another below and just to the left of it can be seen; at about 1070 Hz, 1200 Hz, and 1290 Hz where in addition a second patch near the top can be seen; at about 1400Hz, 1500Hz, 1800Hz where this upper patch becomes isolated; and at five or so frequencies above 5 kHz where only a new, highly localized patch (about 2cm in extent) can be seen in the lower quadrant just right of the panel center. It may be fortuitous, but we can make a simple comparison between this result and that for the mobile patch seen in panel 1. In particular, the panel 1 patch is about 20cm in extent and first appears (resonates) at 420Hz whereas the panel 2 high frequency patch first appears at about 5.2 KHz and is about 2cm in extent. The ratio of the two frequencies is 12 which is close to the inverse ratio of their spatial sizes (10). This relationship would be expected for the resonance of two patches having identical thicknesses but different lateral extent.

In Figs. 7a - 7c is shown the normalized  $|VV^*|$  quantity for three different bands at frequencies below 2KHz. The above mentioned features for these frequencies now appear even more pronounced, presumably due to the frequency

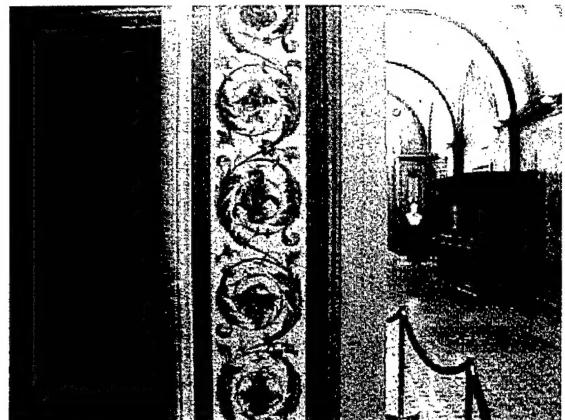


Figure 5 – “Eagle” Panel

averaging (and thus smearing) of the background modal structure of the panel. There also now appear three other mobile patches, one at the panel center, one below that point near the bottom, and one just below and to the right of the second patch from the left. Finally in Fig. 8 is shown the normalized  $|VV^*|$  quantity for the entire band, 770Hz to 5KHz. Here all of the above features can be seen. This figure seems to indicate a total defect area of about 30-40%, a number consistent with the 50% level estimated with the tap tests. In addition, the broadband motion now clearly reveals two vertical discontinuities, the sharpness of which suggests they are connected to the structural design of the panel.

## POST PROCESSING

In the following, we present the result of applying several post-processing algorithms to the LDV data. In Fig. 9 we show the results of applying a 1-D Fourier spatial transform on the velocity data over the band 10Hz to 8KHz. This used the data along a vertical line about 20cm from the left edge of panel 2. Imposed on the figure is the dispersion line for a vertical shear wave traveling in the plaster at a speed of about 700m/s. One can see significant energy out to this shear line indicating that our earlier speculation of predominate shear wave propagation even at the higher frequencies is correct.

We also considered the application of a cross-correlation algorithm which we have used for another application. In this approach, the LDV measured velocity at each point ( $\vec{r}$ ) is multiplied by the complex conjugate of that at a reference point ( $\vec{r}'$ ). The function would be of the form  $|V(\vec{r})V^*(\vec{r}')|$ . For panel 2, we show in Fig. 10 this quantity for one particular  $\vec{r}'$  for the band 770 Hz to 1500 Hz. This should be compared to Fig. 7a, which is a special case of the function above, namely the autocorrelation function, i.e. when  $\vec{r} = \vec{r}'$ . In our experience, the cross correlation algorithm can, in some cases, extract low-lying features missed by the autocorrelation approach.

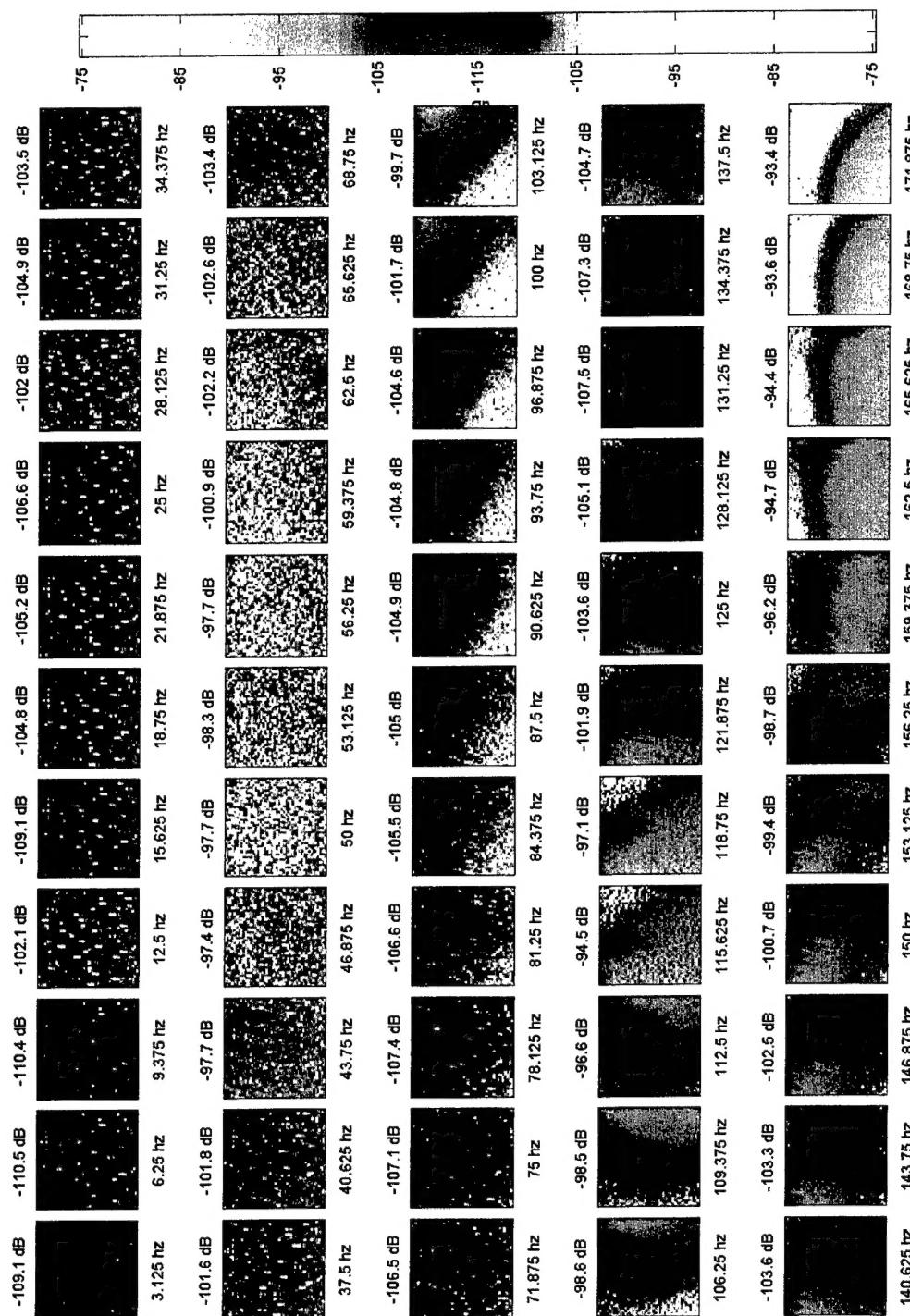
Finally, we attempted to invert the LDV measured velocity field to obtain a map of the elastic modulus using an algorithm we have developed based on the equations of motion. The mapping resulting from the inversion is shown in Fig. 11. Based upon our experience in applying this algorithm, we believe the strong red features are artifacts resulting from operating our wave-based algorithm on a modally-excited structure. We believe, however, that the deep blue feature on the

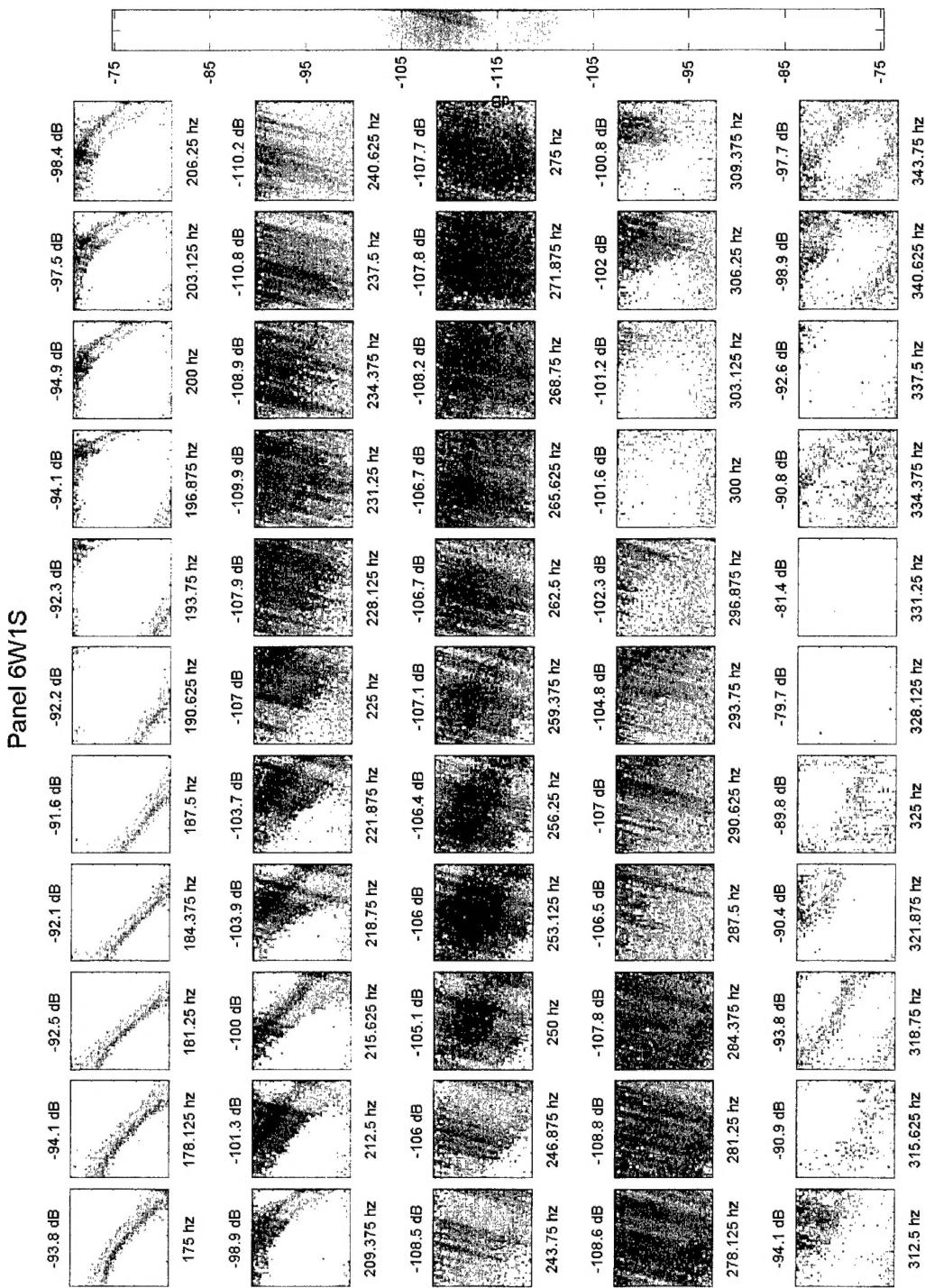
left is real and indicates that this patch has a stiffness roughly one half that of the overall panel.

## CONCLUSIONS

The results discussed above for panel 1 and panel 2 suggest that LDV scans of panels excited locally with a broadband actuator can provide important information about the layered panel integrity. One can also intuit that it would be beneficial to collect such data for more than one local actuator position. This seems prudent since in general one cannot be certain that any particular local actuation scheme will result in elastic energy distributed more or less uniformly throughout the panel.

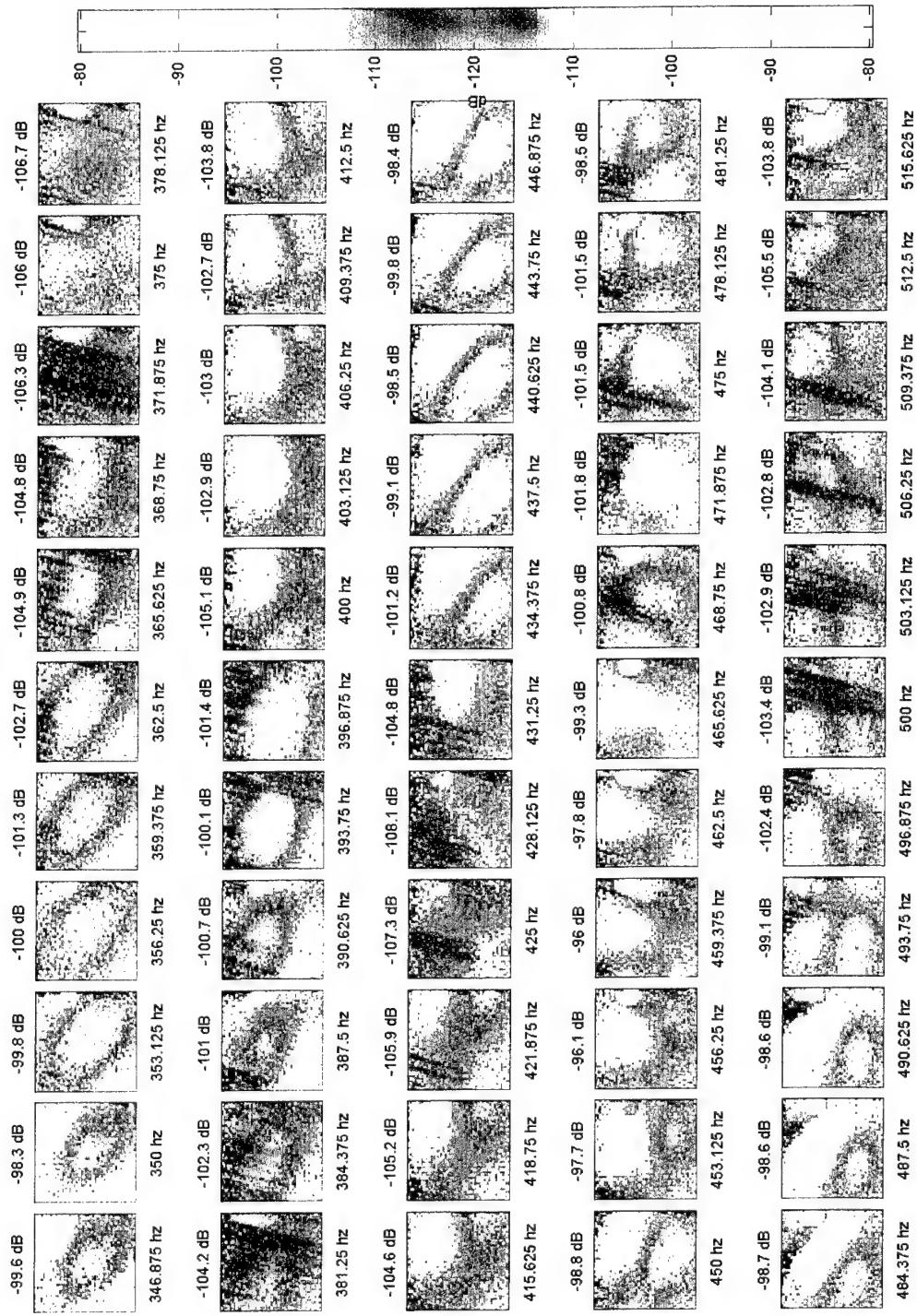
**Figure 2a**





Single Surface Scan file: FFT1\_50X50POINTS\_LDV\_XFN plotted: 21-Jan-2003 vignola

Panel 6W1S



Single Surface Scan file: FFT1\_50X50POINTS\_LDV/XFN plotted: 21-Jan-2003 vignola

Figure 2c

Panel 6W1S

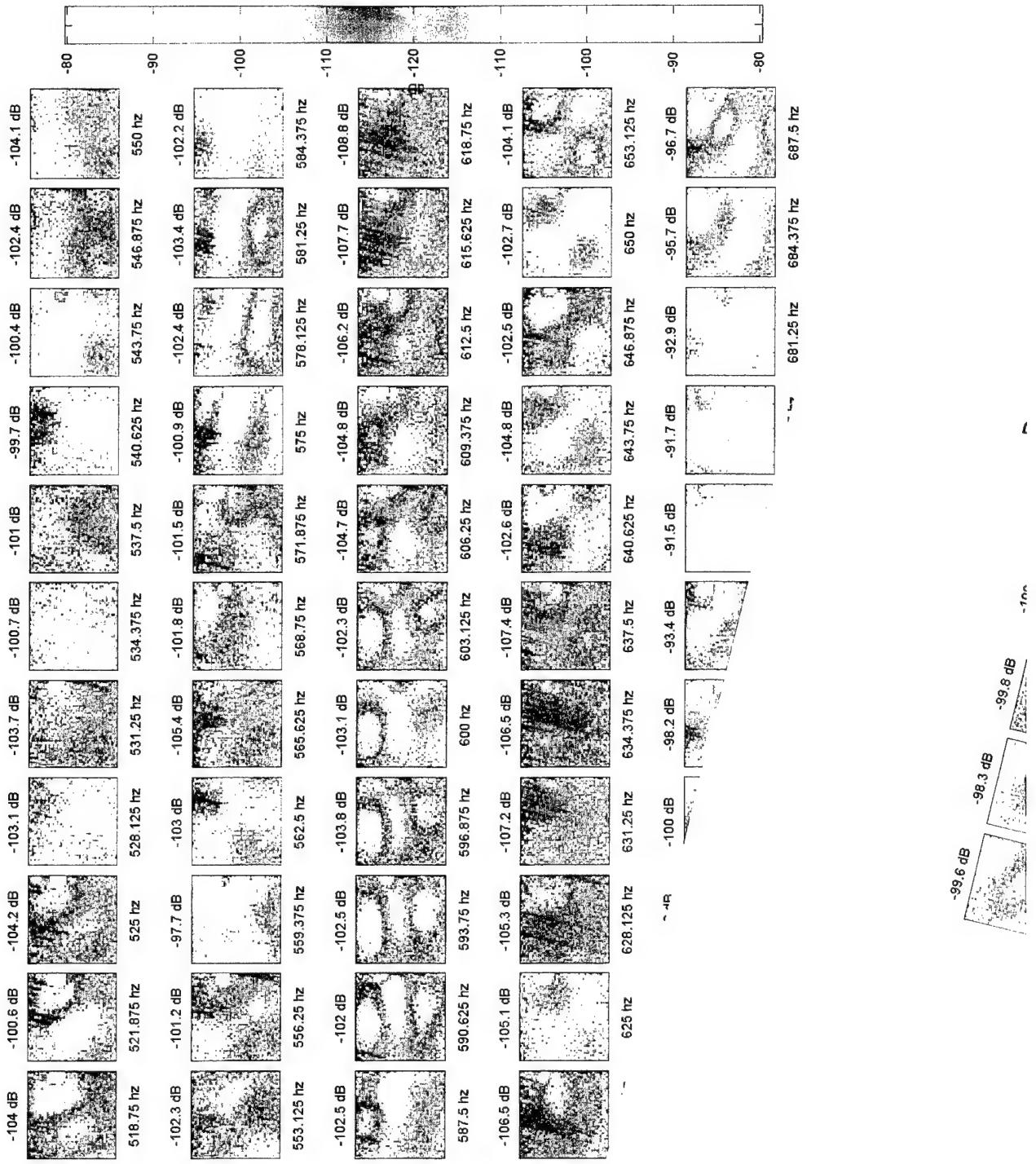




Figure 2e

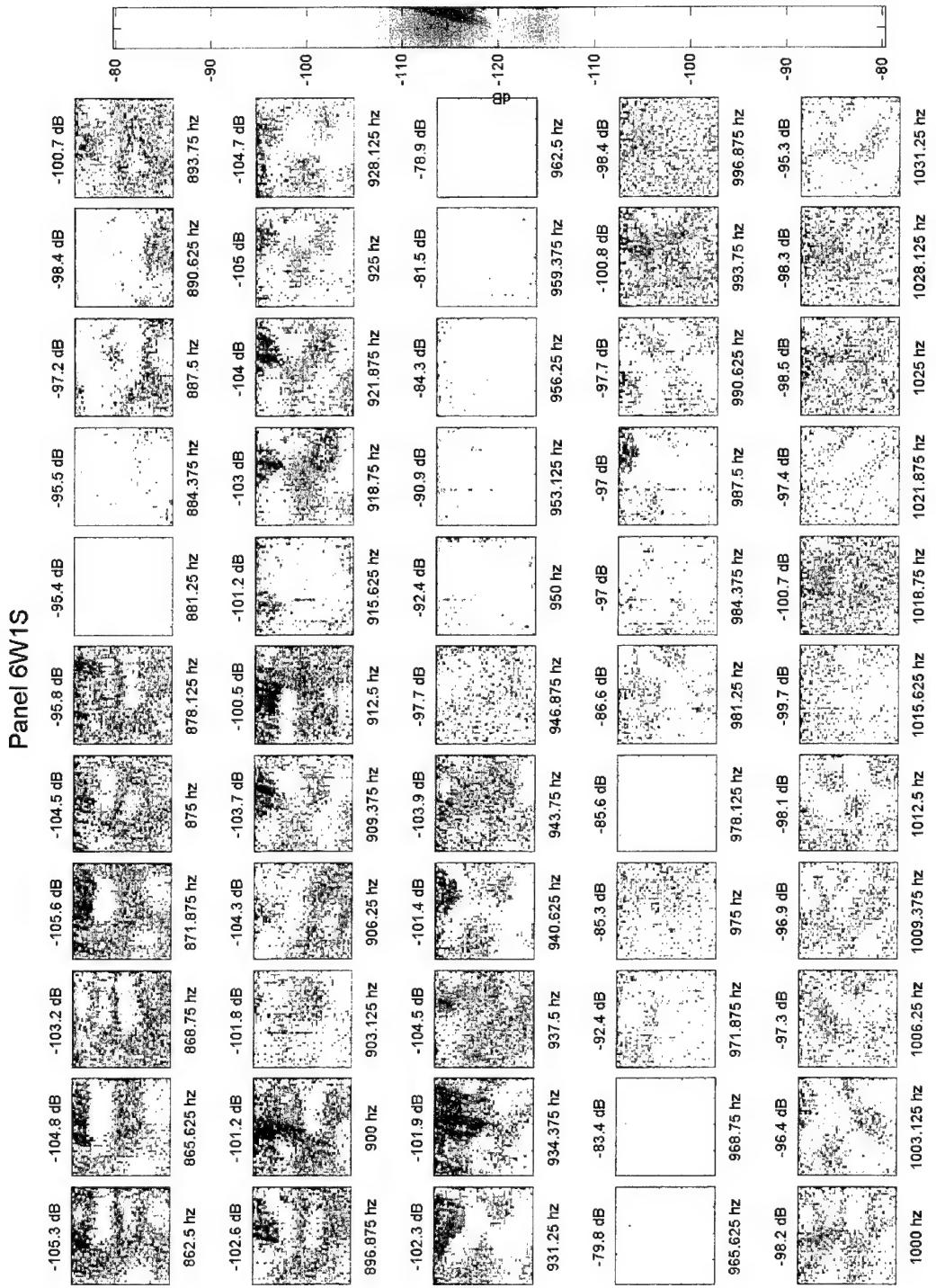
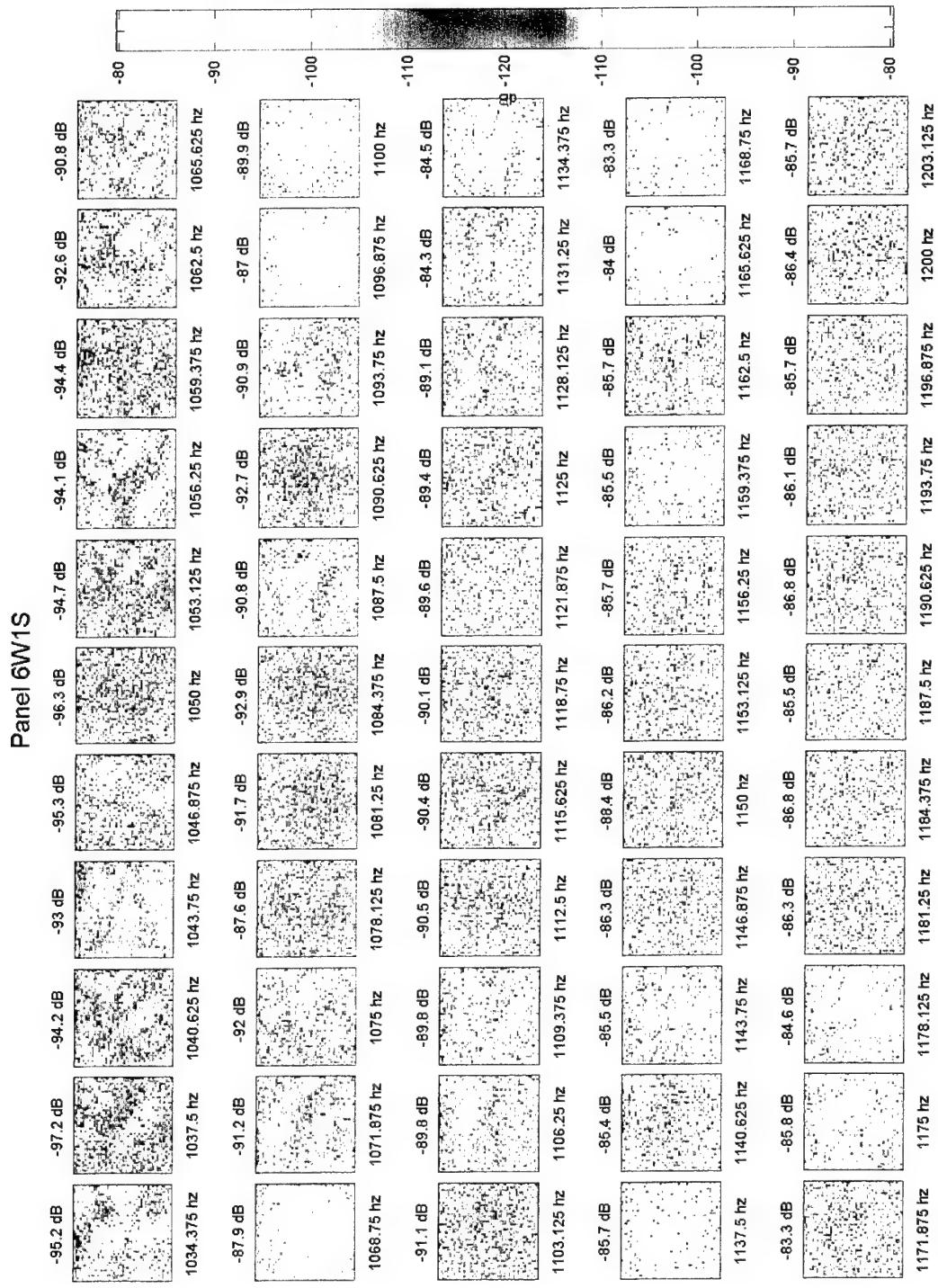


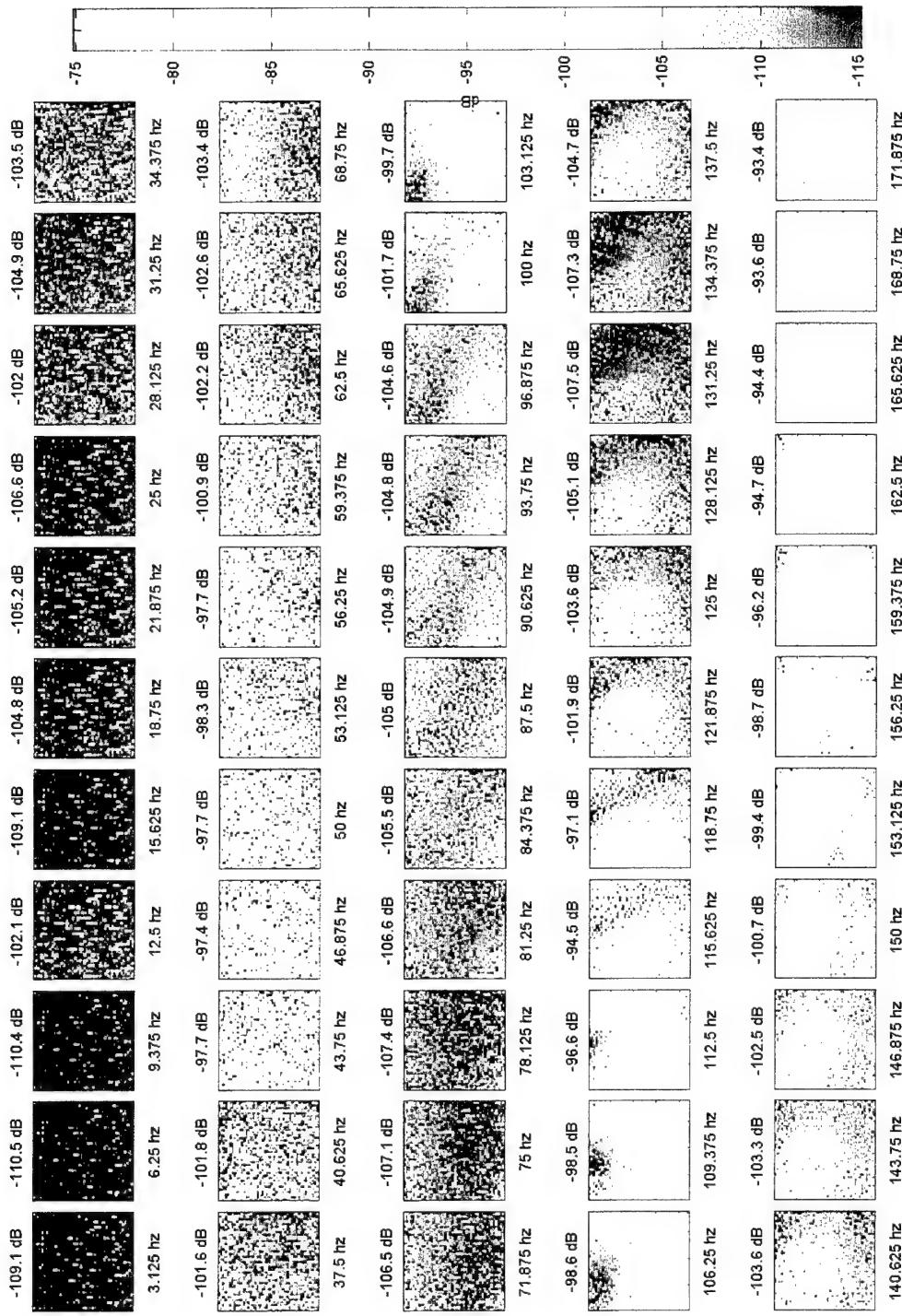
Figure 2f

Single Surface Scan file: FFT1\_50x50POINTS\_LDV/XFN plotted: 21-Jan-2003 vignola



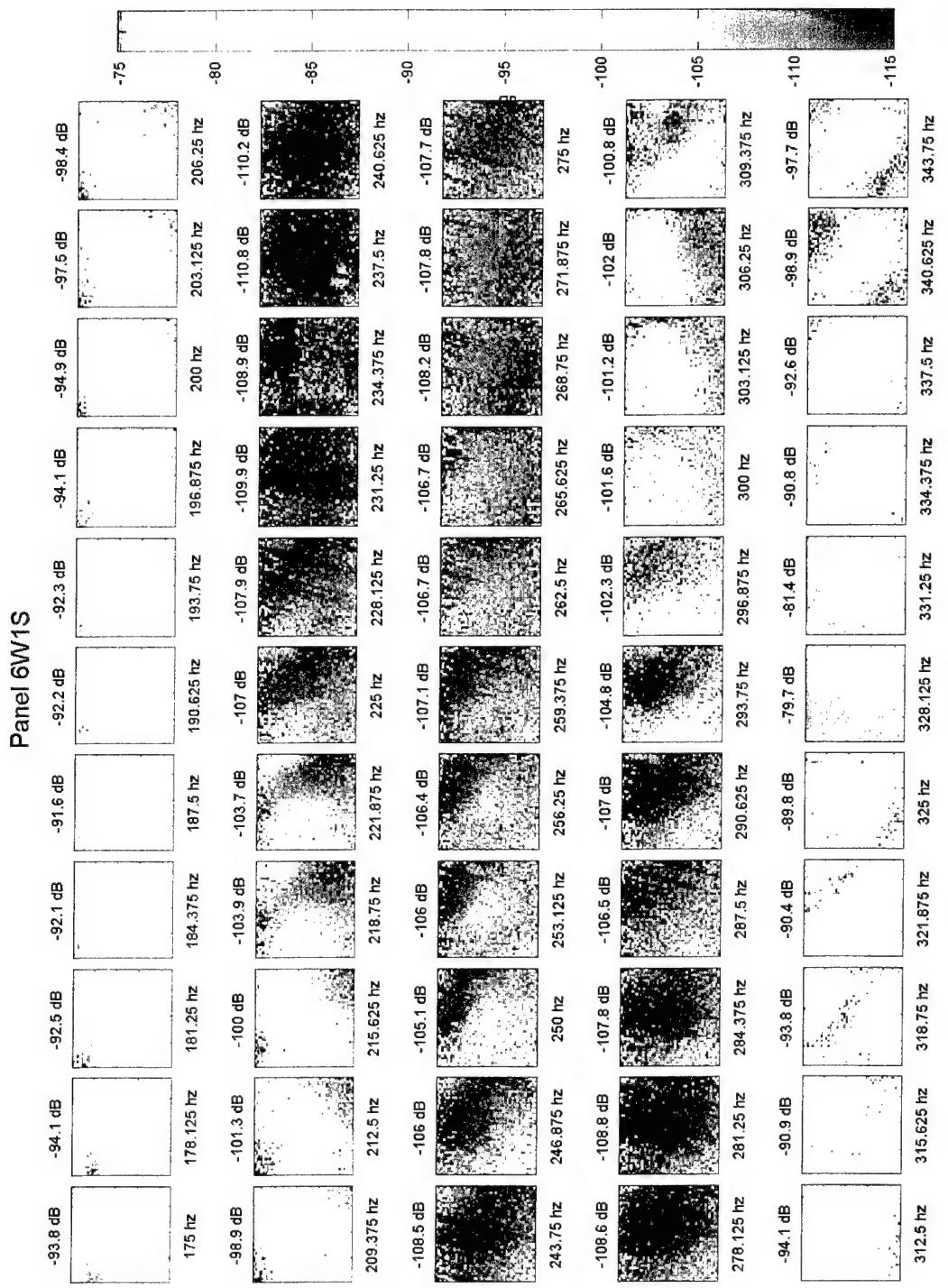
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**Figure 2g**



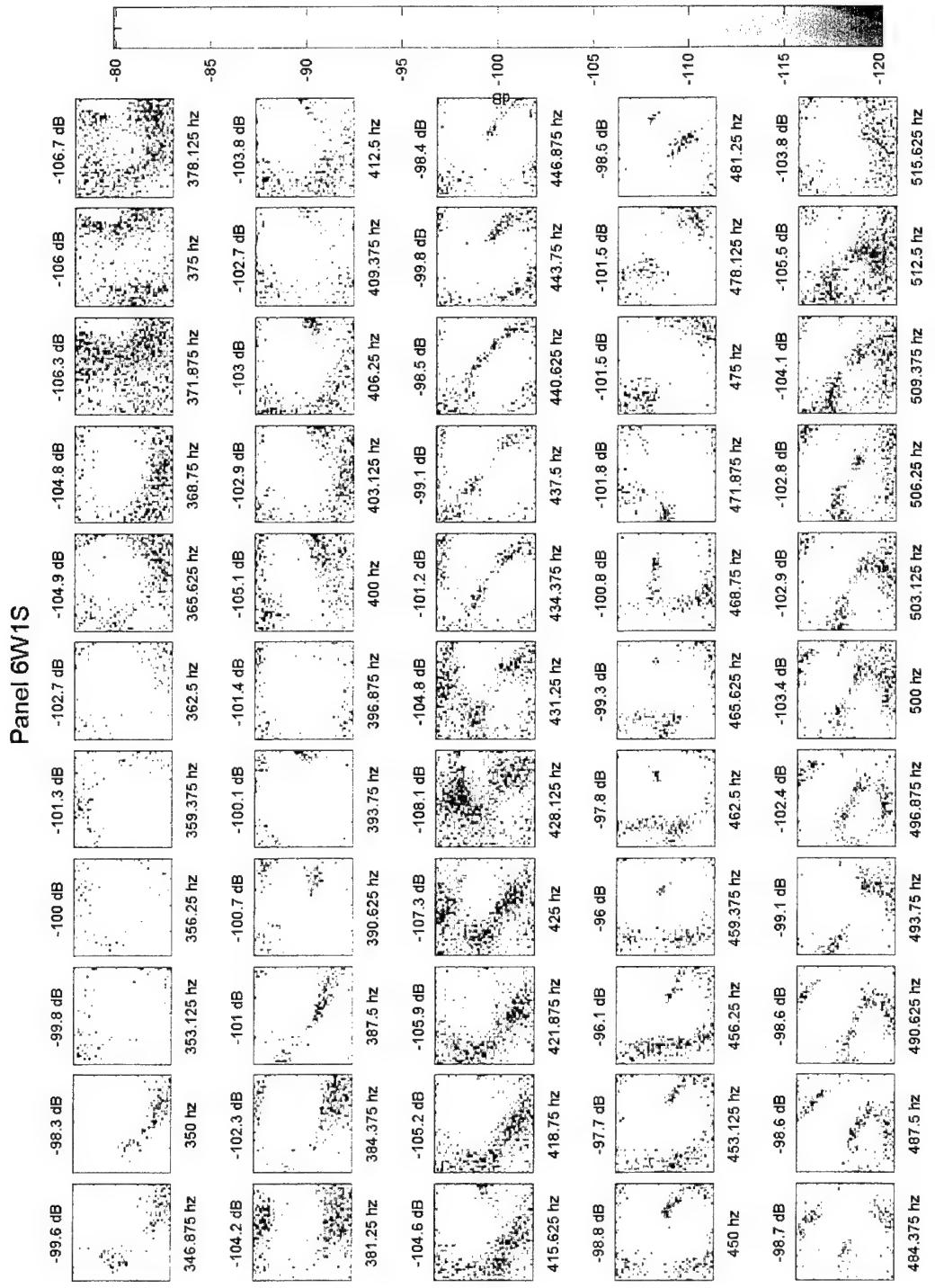
Single Surface Scan file: FFT1\_50x50POINTS\_LDVXFN plotted: 21-Jan-2003 vignola

Figure 3a



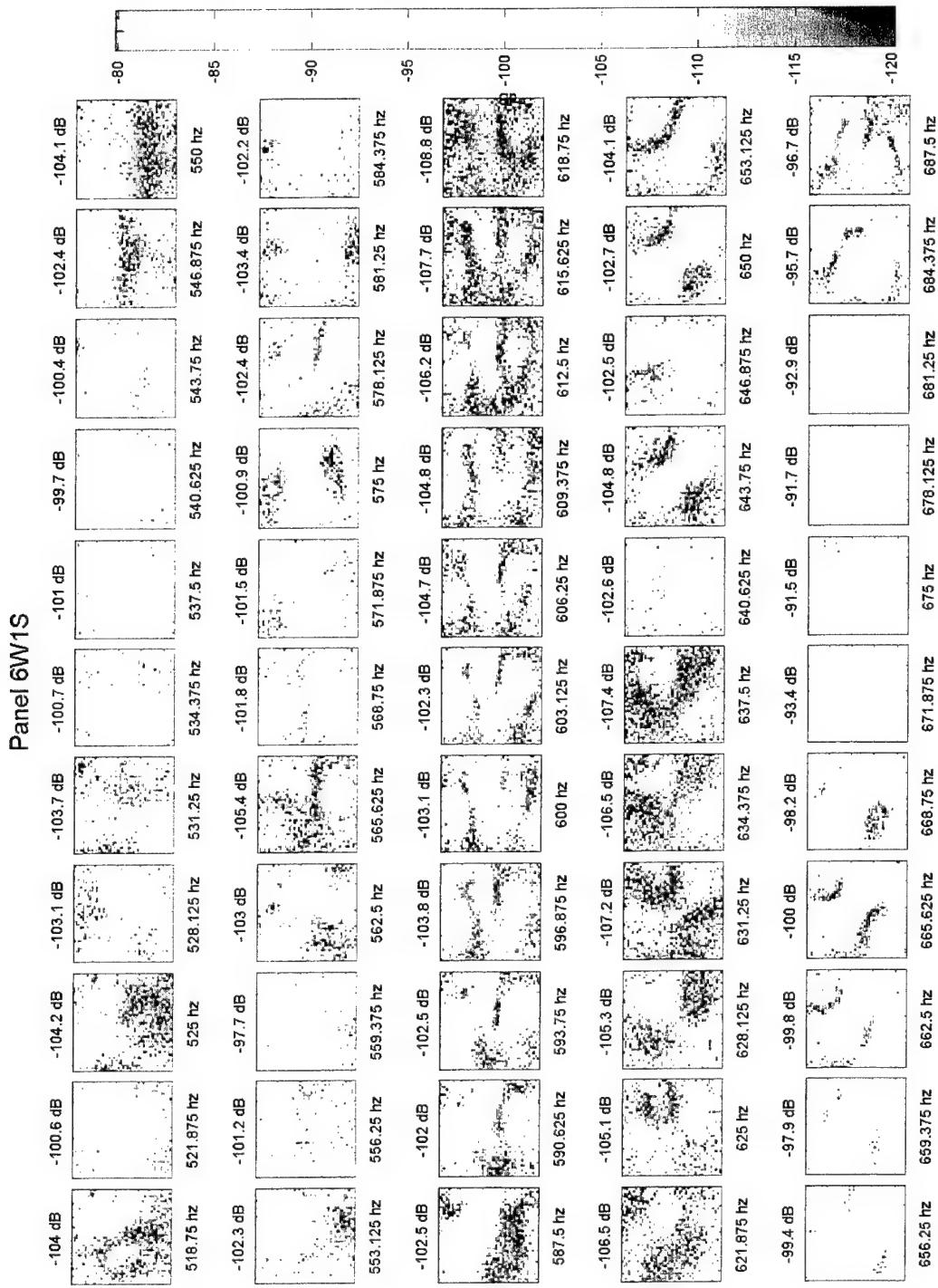
**Figure 3b**

Single Surface Scan file: FFT1\_50X50POINTS\_LDV\_XFN plotted: 21-Jan-2003 vignola



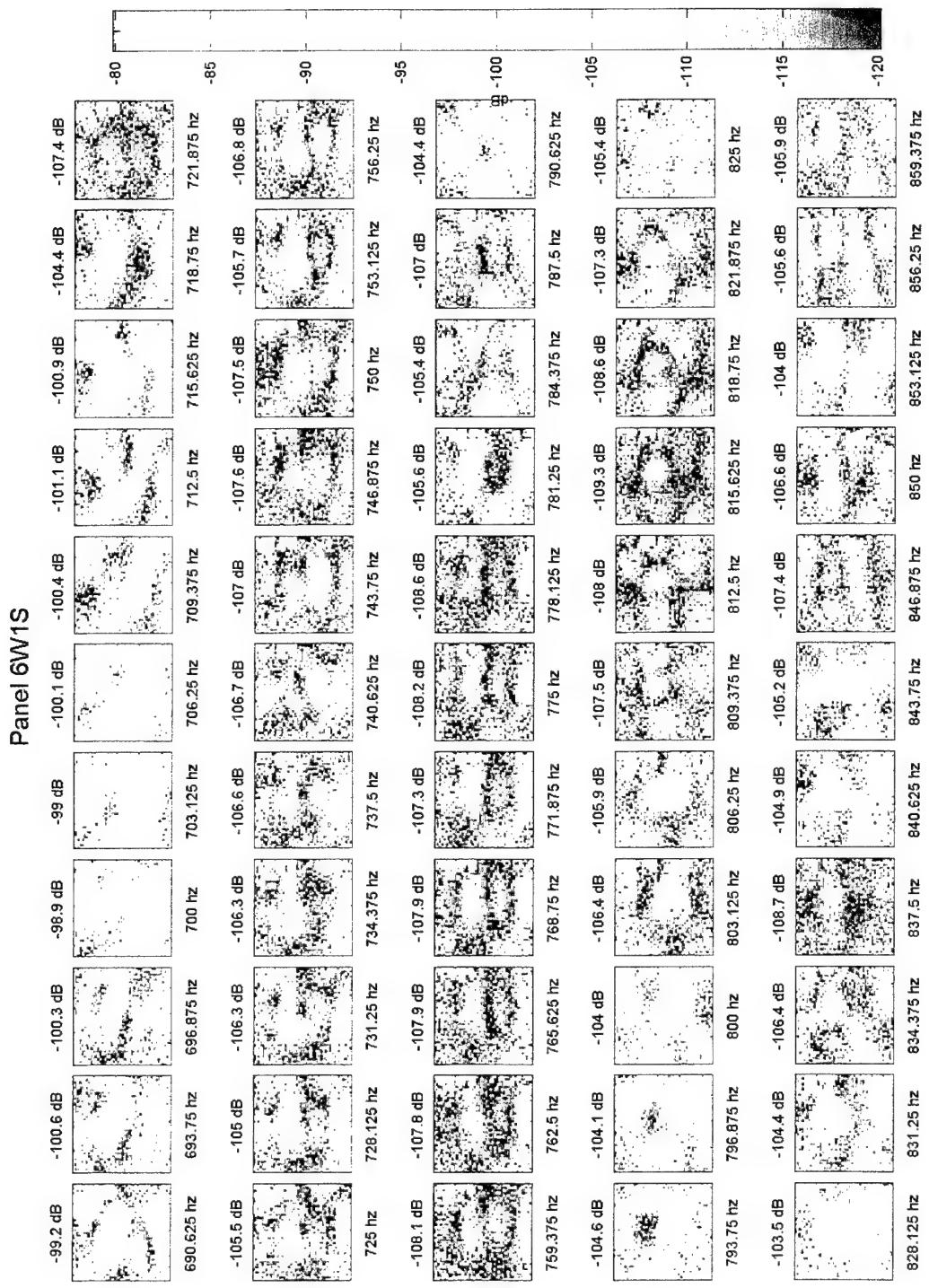
Single Surface Scan file: FFT1\_50X60POINTS\_LDV/XFN plotted: 21-Jan-2003 vignola

**Figure 3c**



Single Surface Scan file: FFT1\_50X50POINTS\_LDV.XFN plotted: 21-Jan-2003 vignola

**Figure 3d**

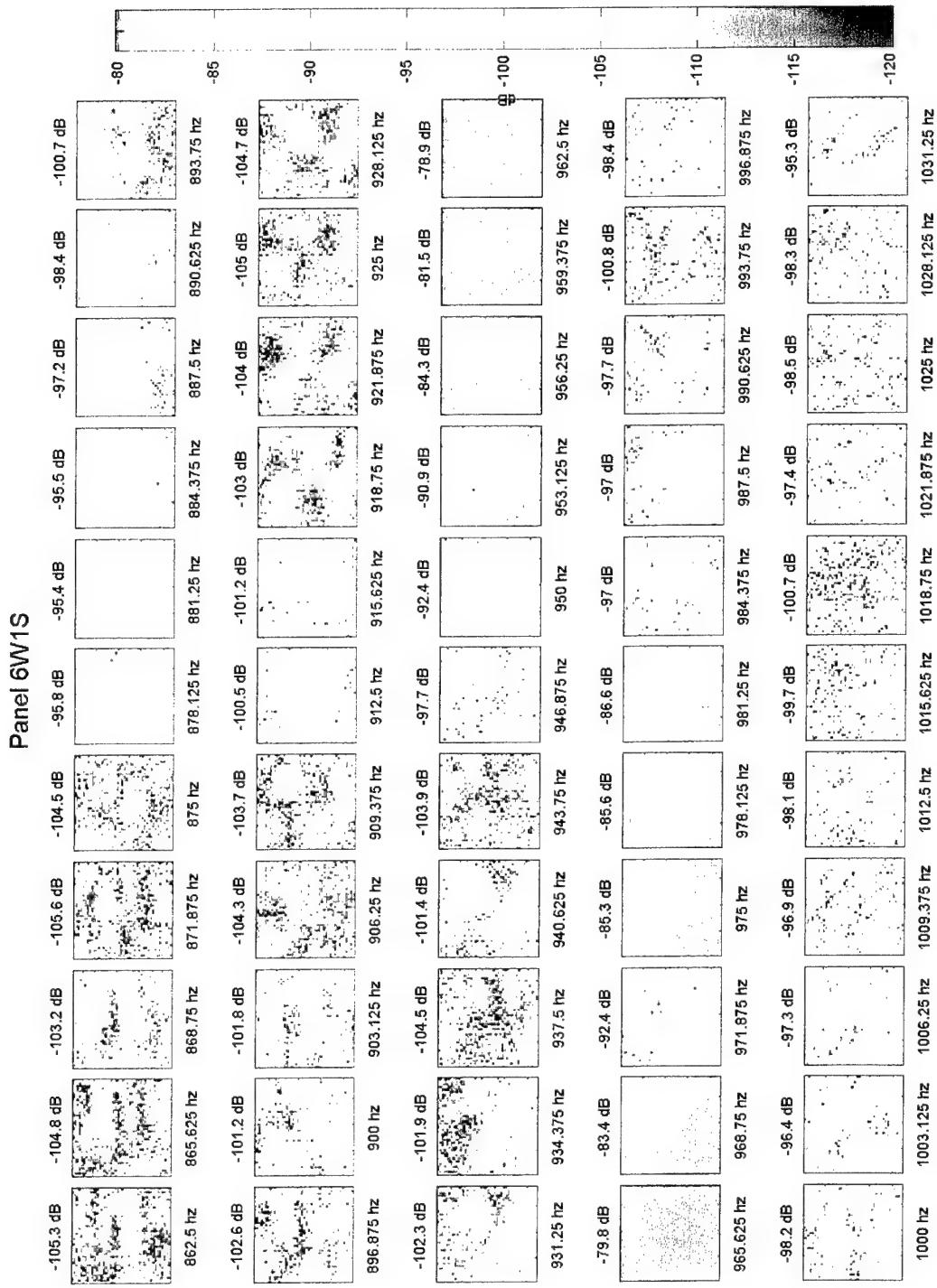


Single Surface Scan file: FFT1\_50x50POINTS\_LDV\_XFN plotted: 21-Jan-2003 vignola

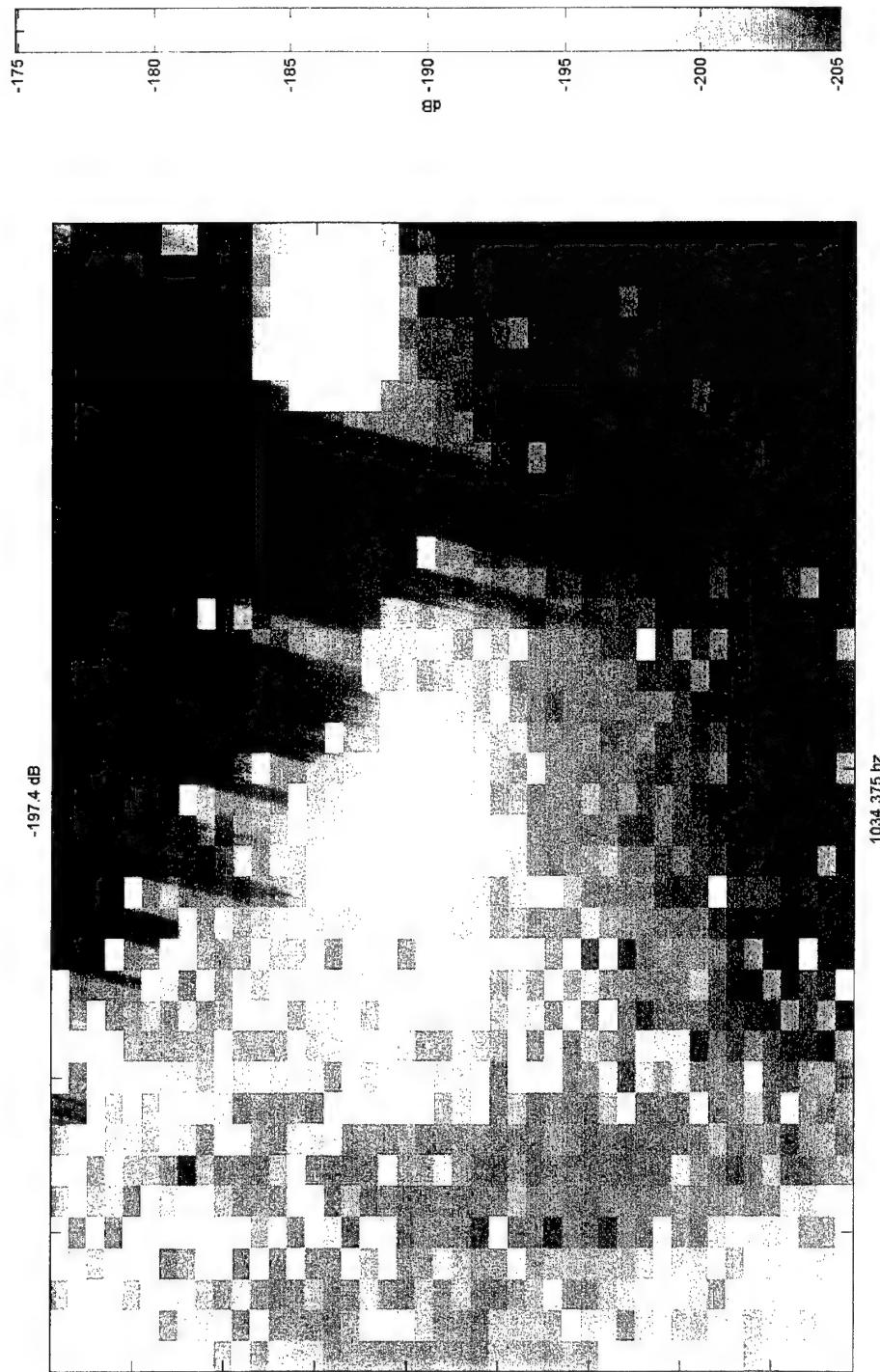
Figure 3e

Figure 3f

Single Surface Scan file: FFT1\_50X50POINTS LDVXFN plotted: 21-Jan-2003 vignola



band: 337.5 Hz to 400Hz



Single Surface Scan file: FFT1\_50X50POINTSLDV.XFN plotted: 22-Jan-2003 vignola

Figure 4a

band: 400 Hz to 500Hz

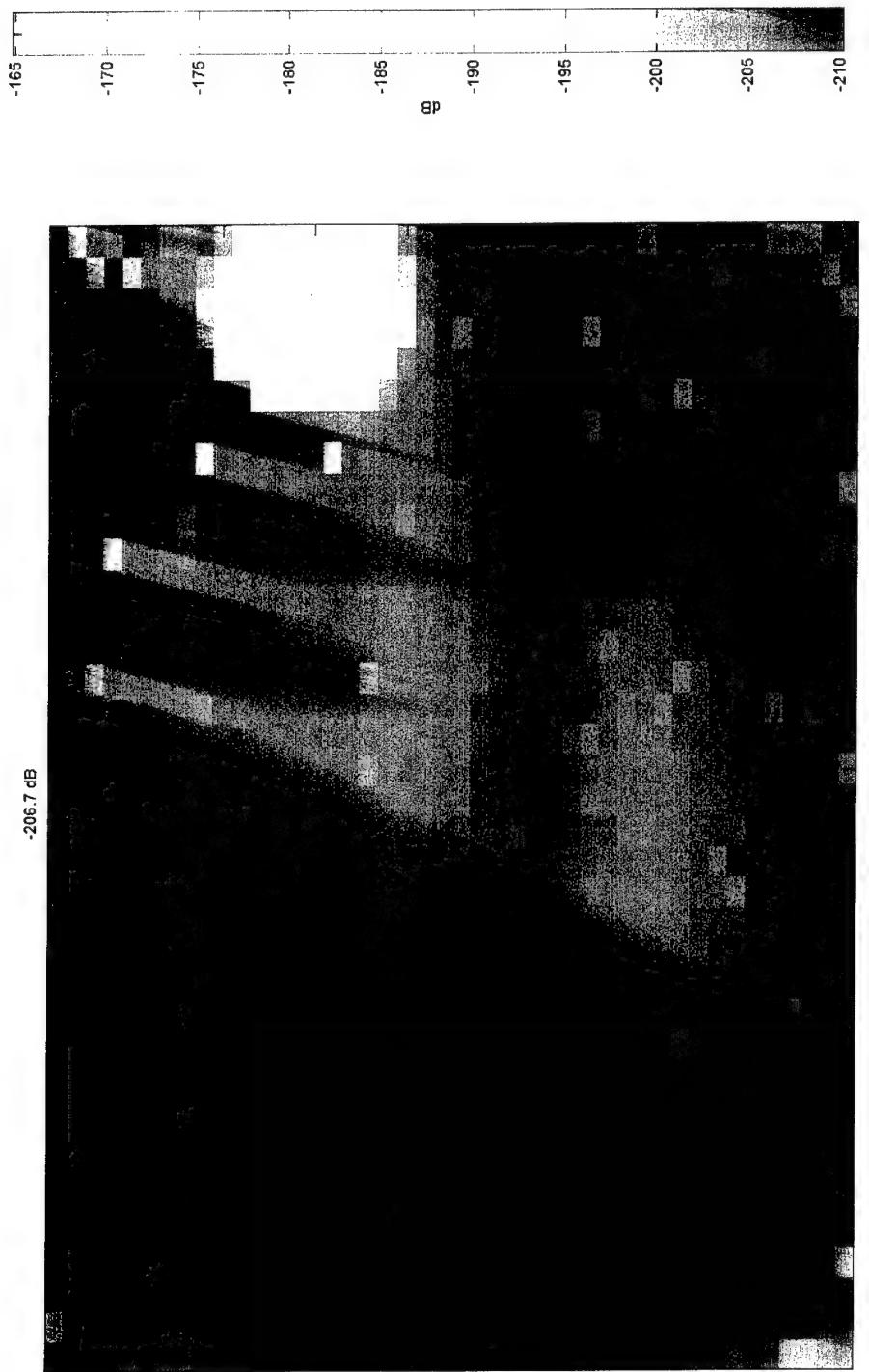


Figure 4b

band: 337.5 Hz to 940.625Hz

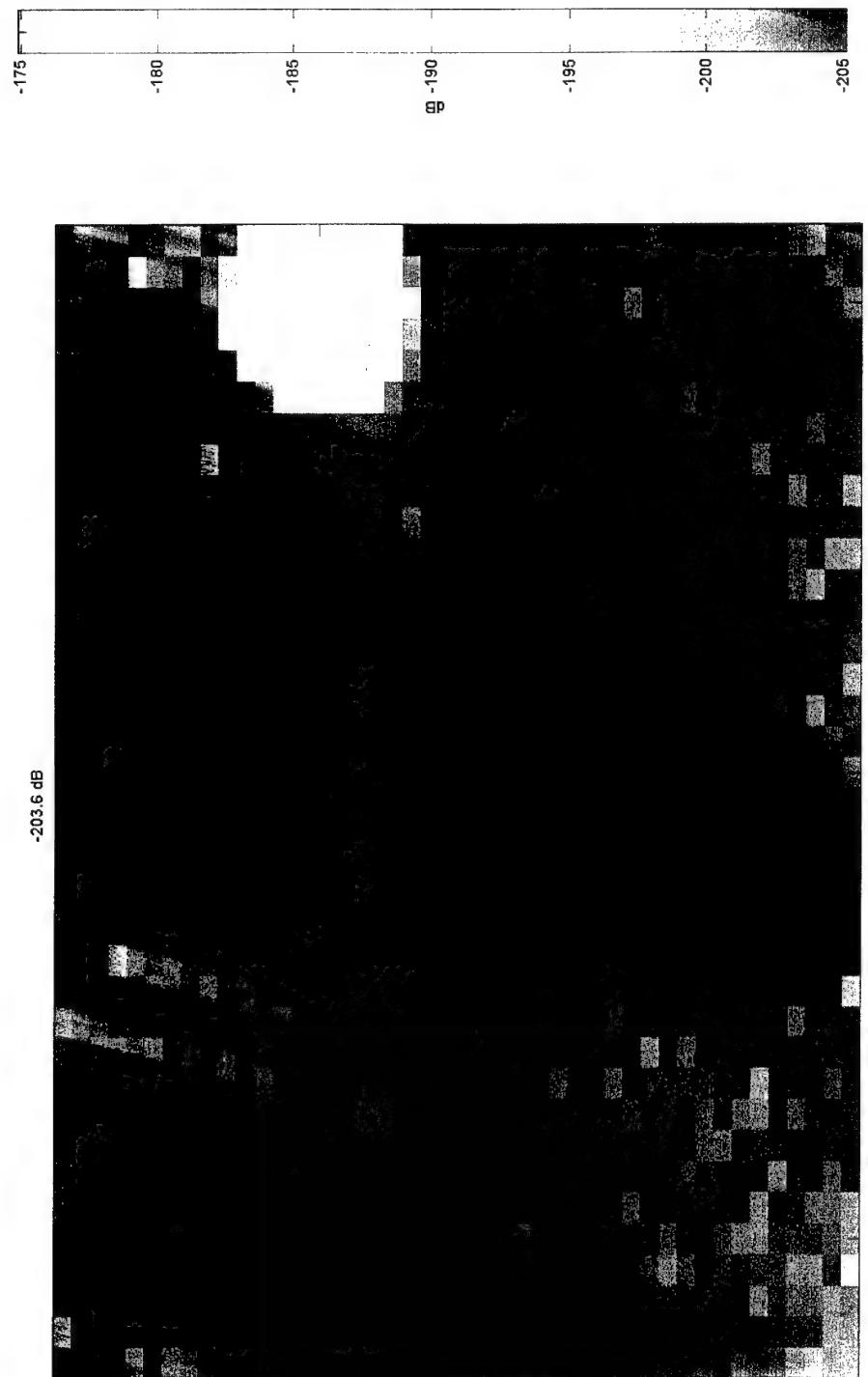
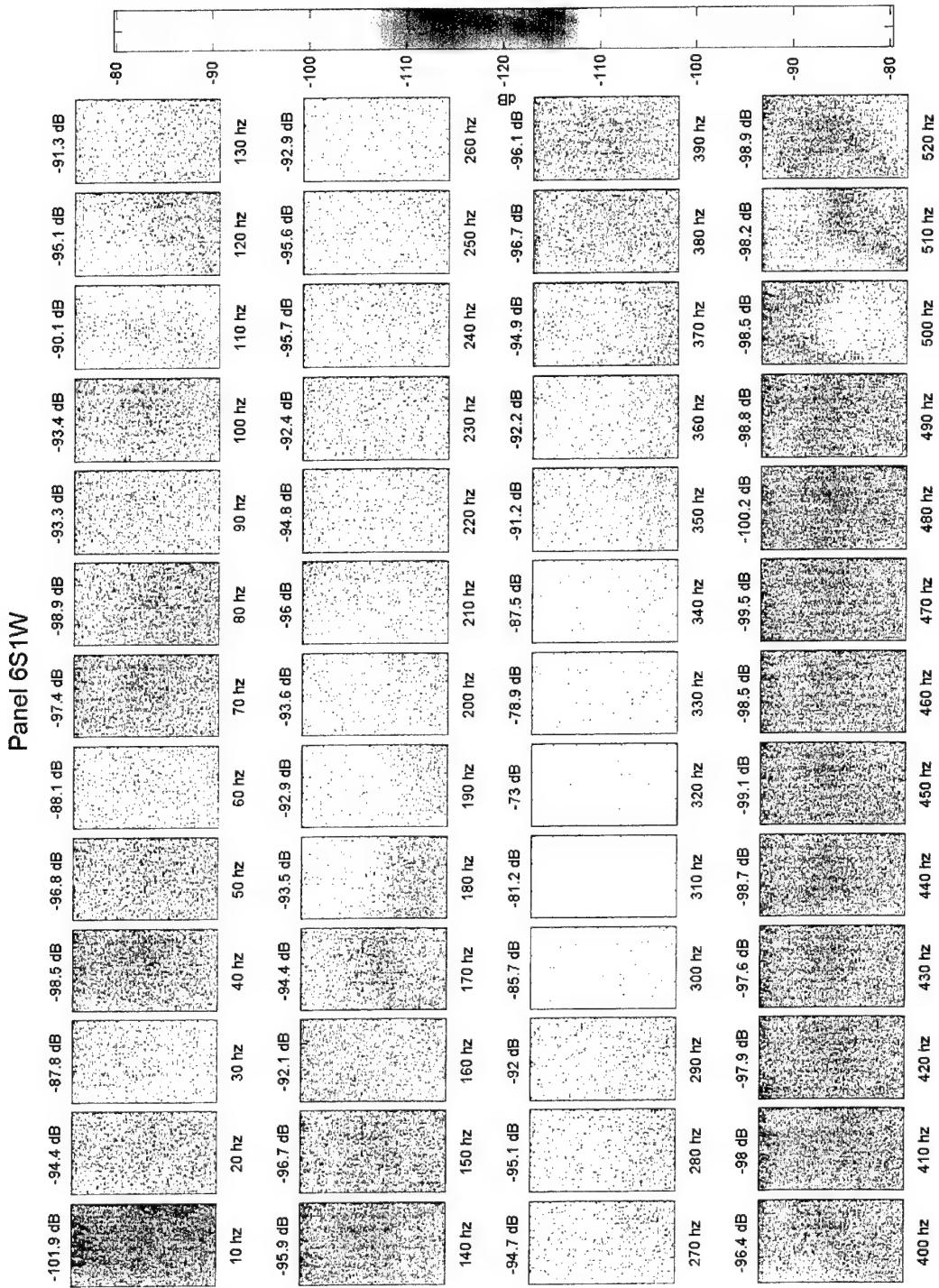
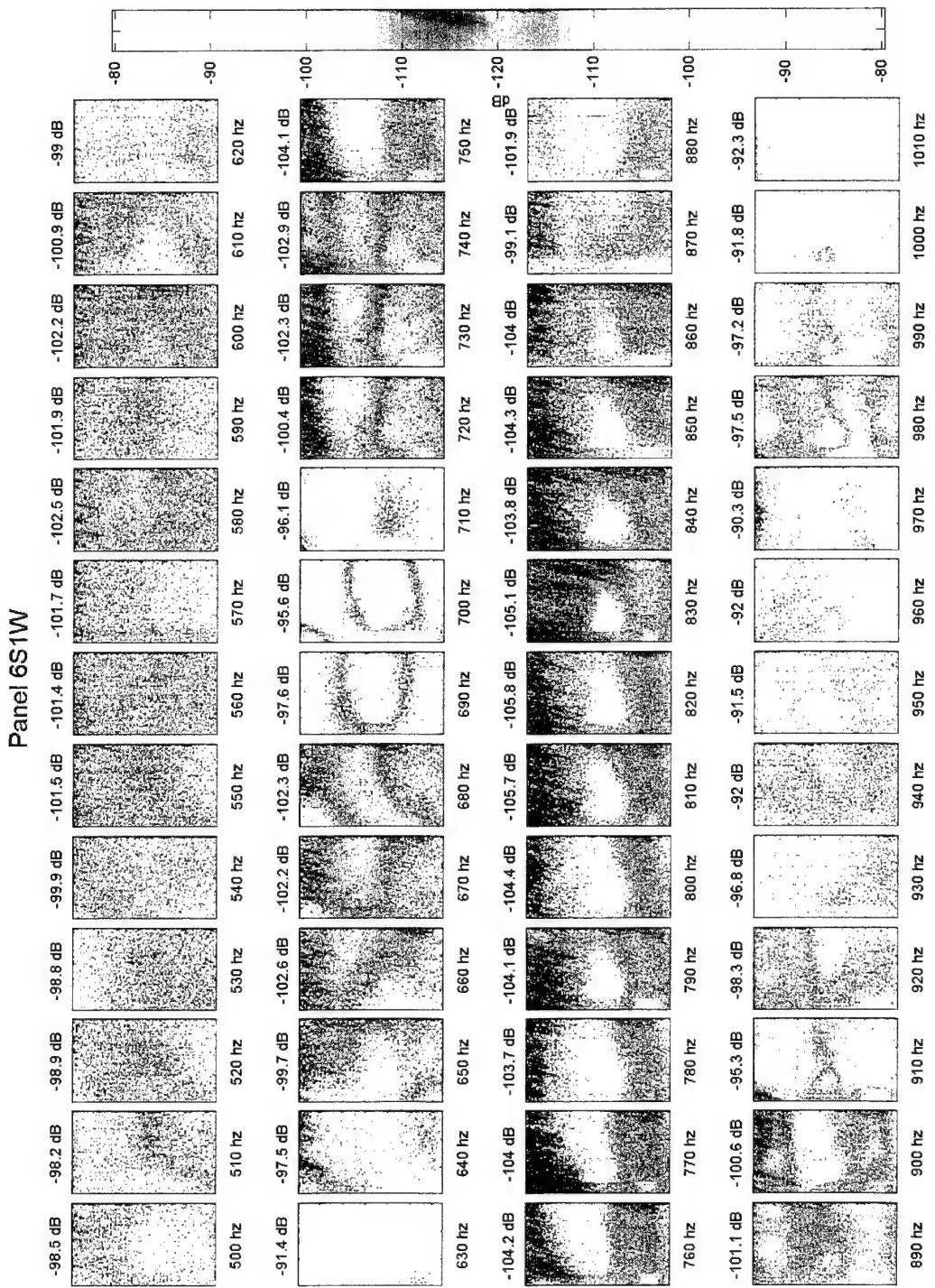


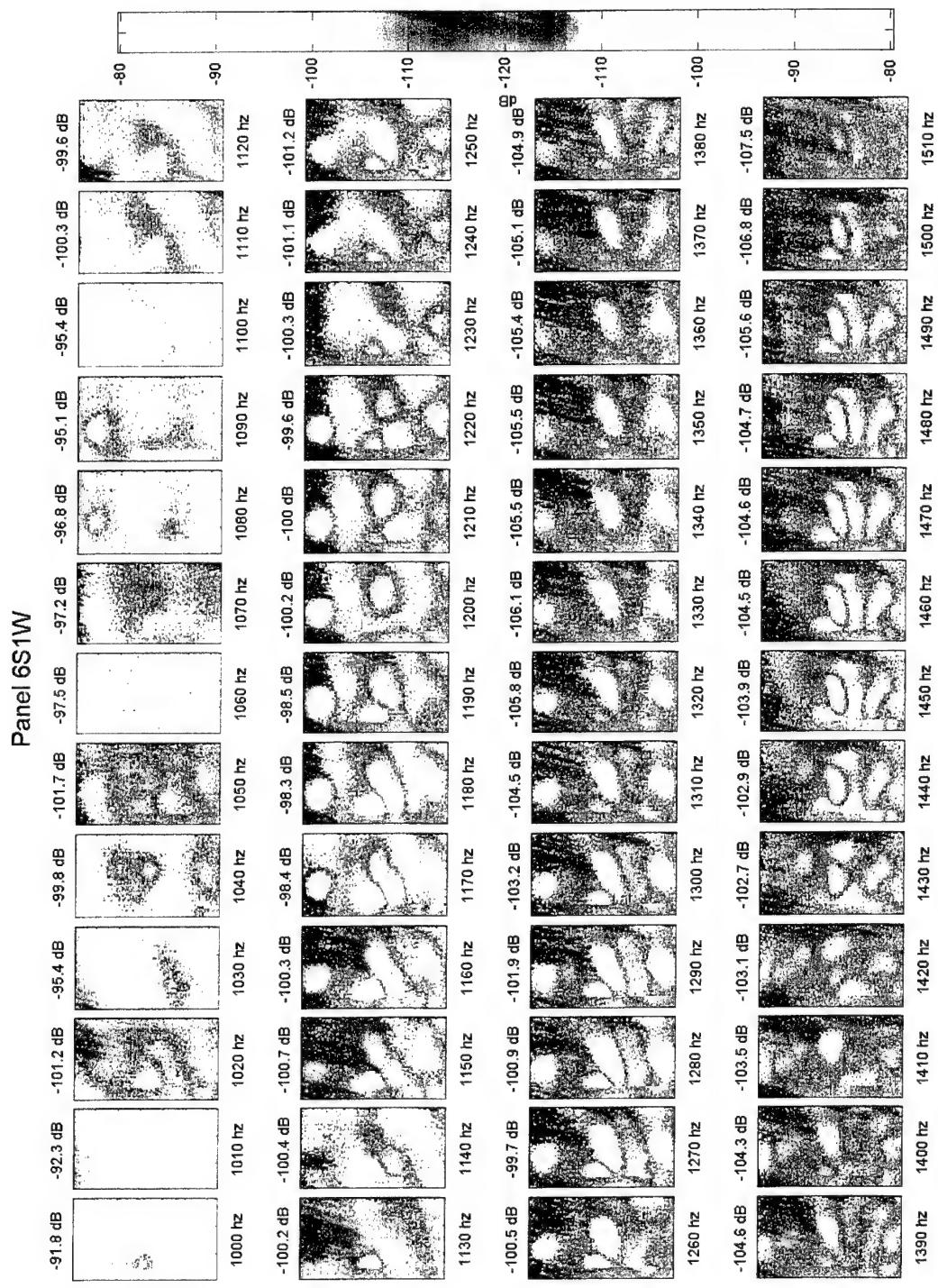
Figure 4c



Single Surface Scan file: SCAN\_LAST\_3UNV\_LDV\_XFN plotted: 22-Jan-2003 vignola

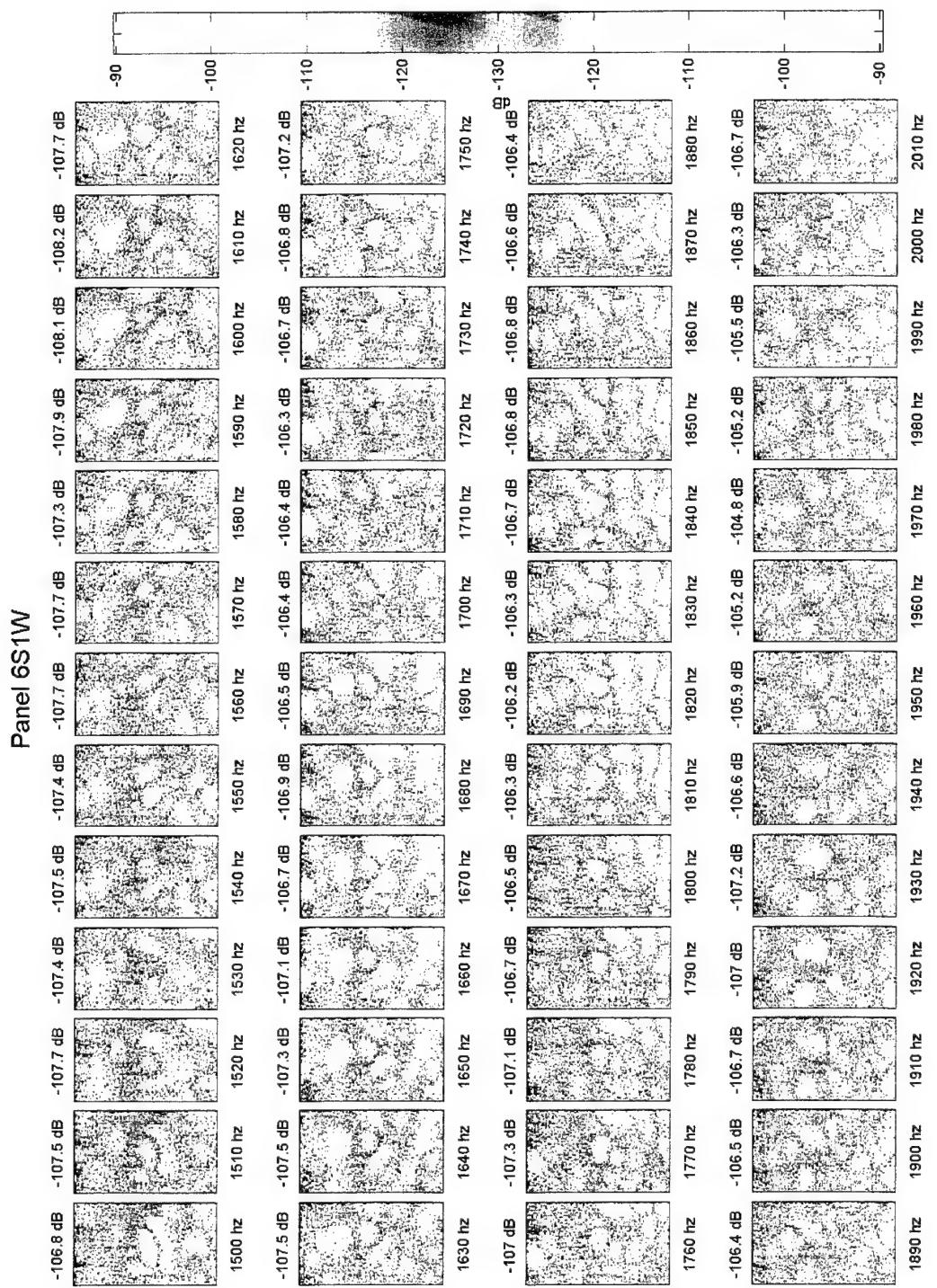
Figure 6a





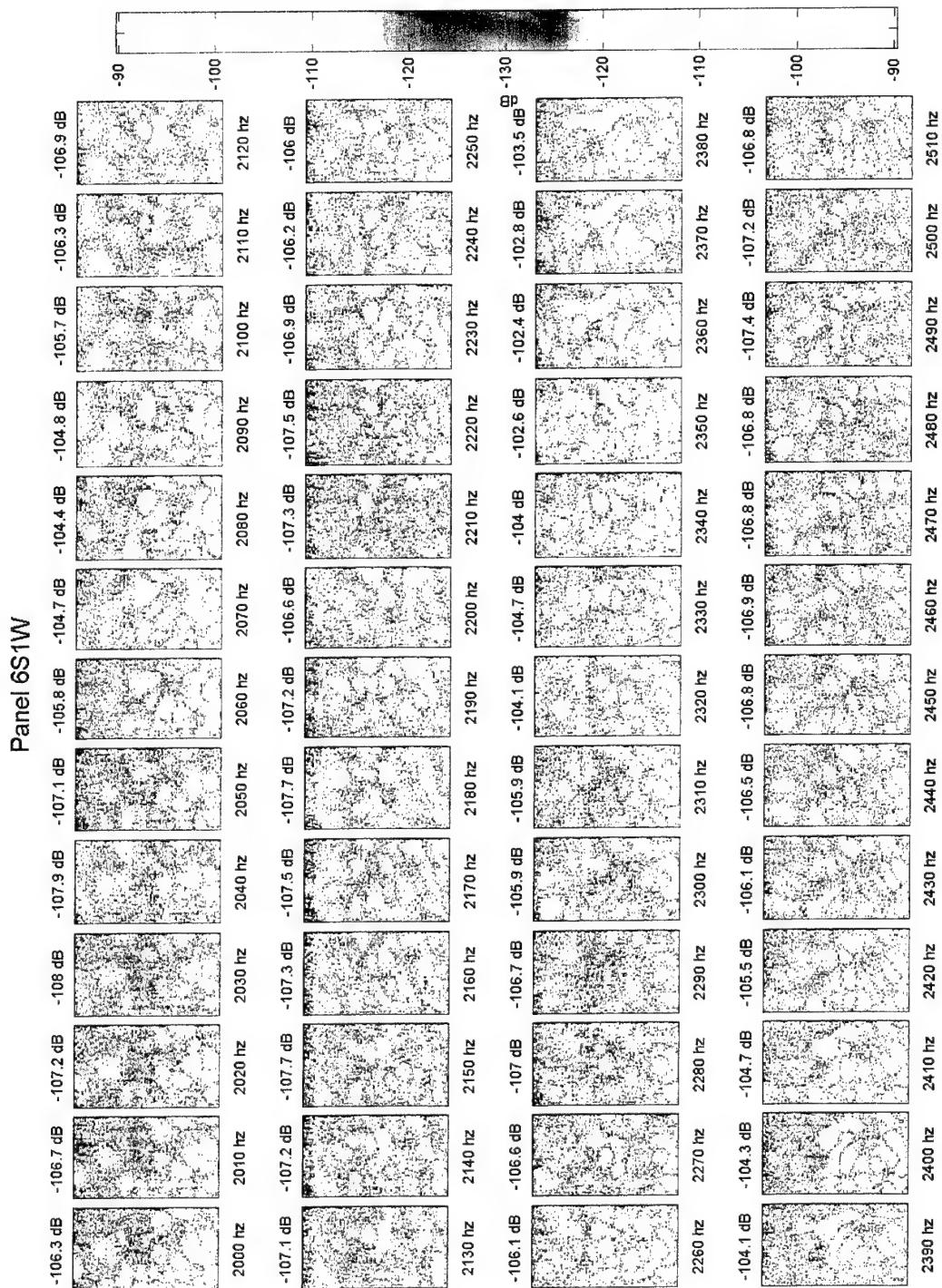
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**Figure 6c**



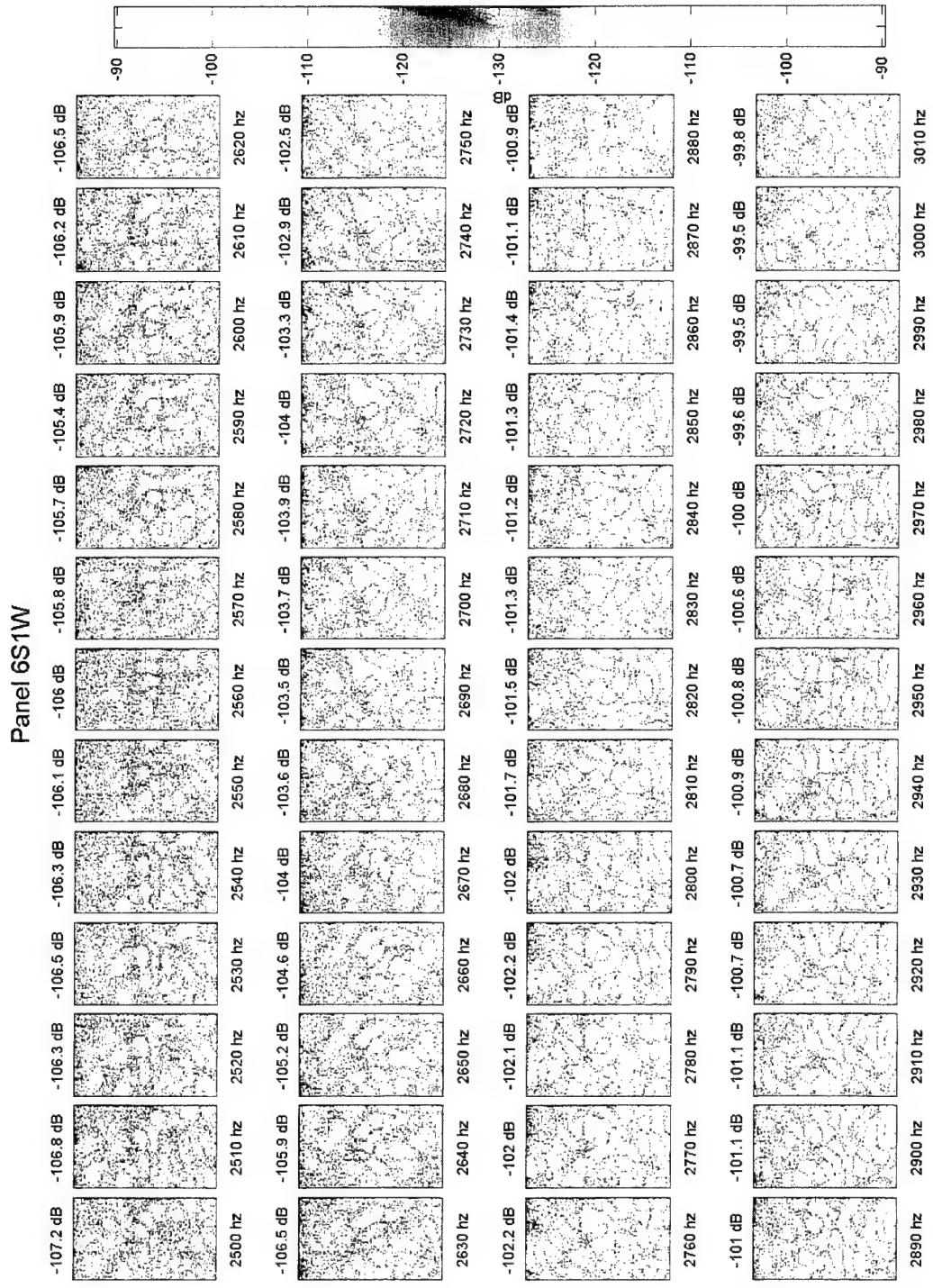
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**Figure 6d**

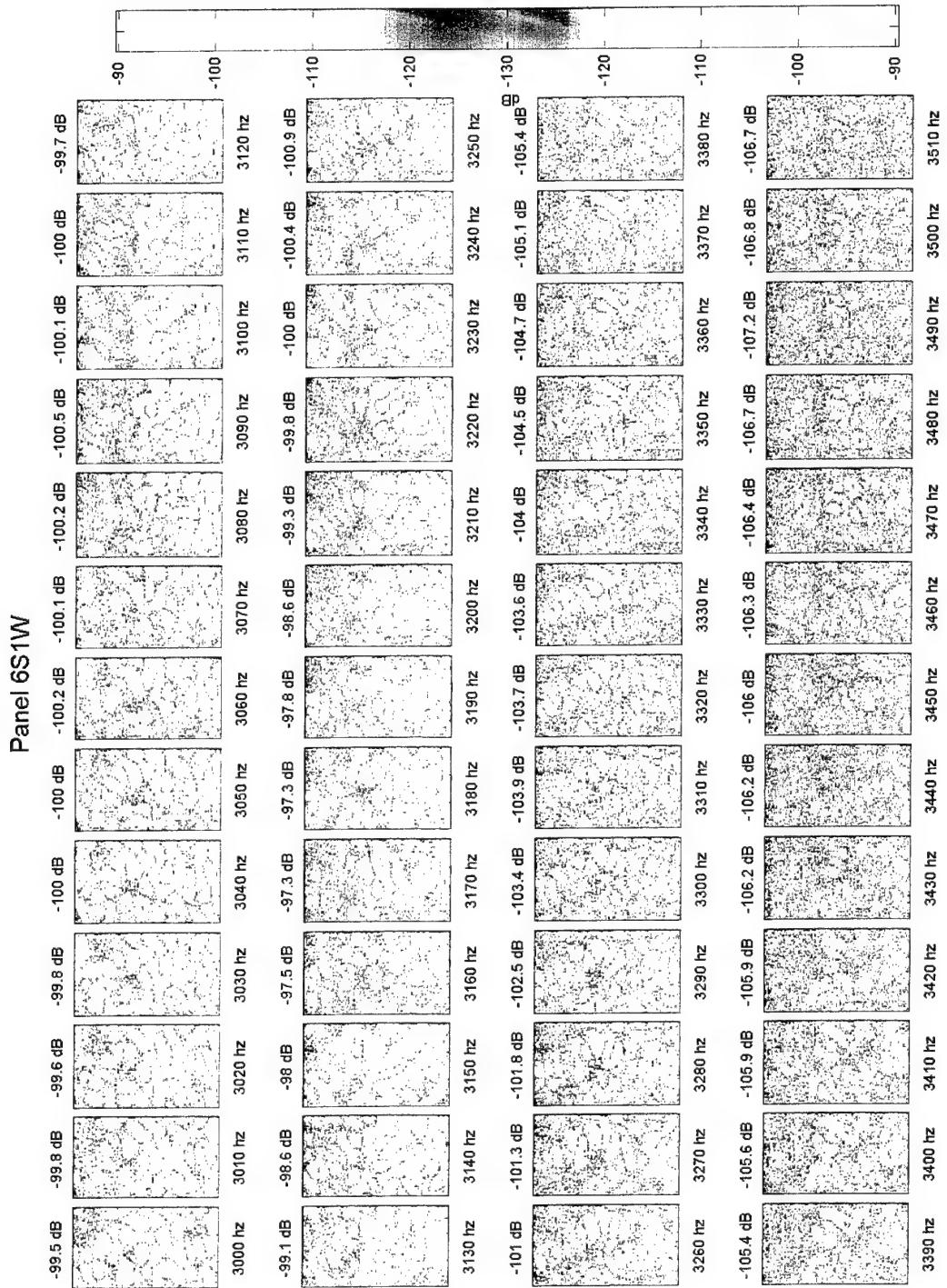


Single Surface Scan file: SCAN\_LAST\_3UNV\_LDV\_XFN plotted: 22-Jan-2003 vignola

Figure 6e

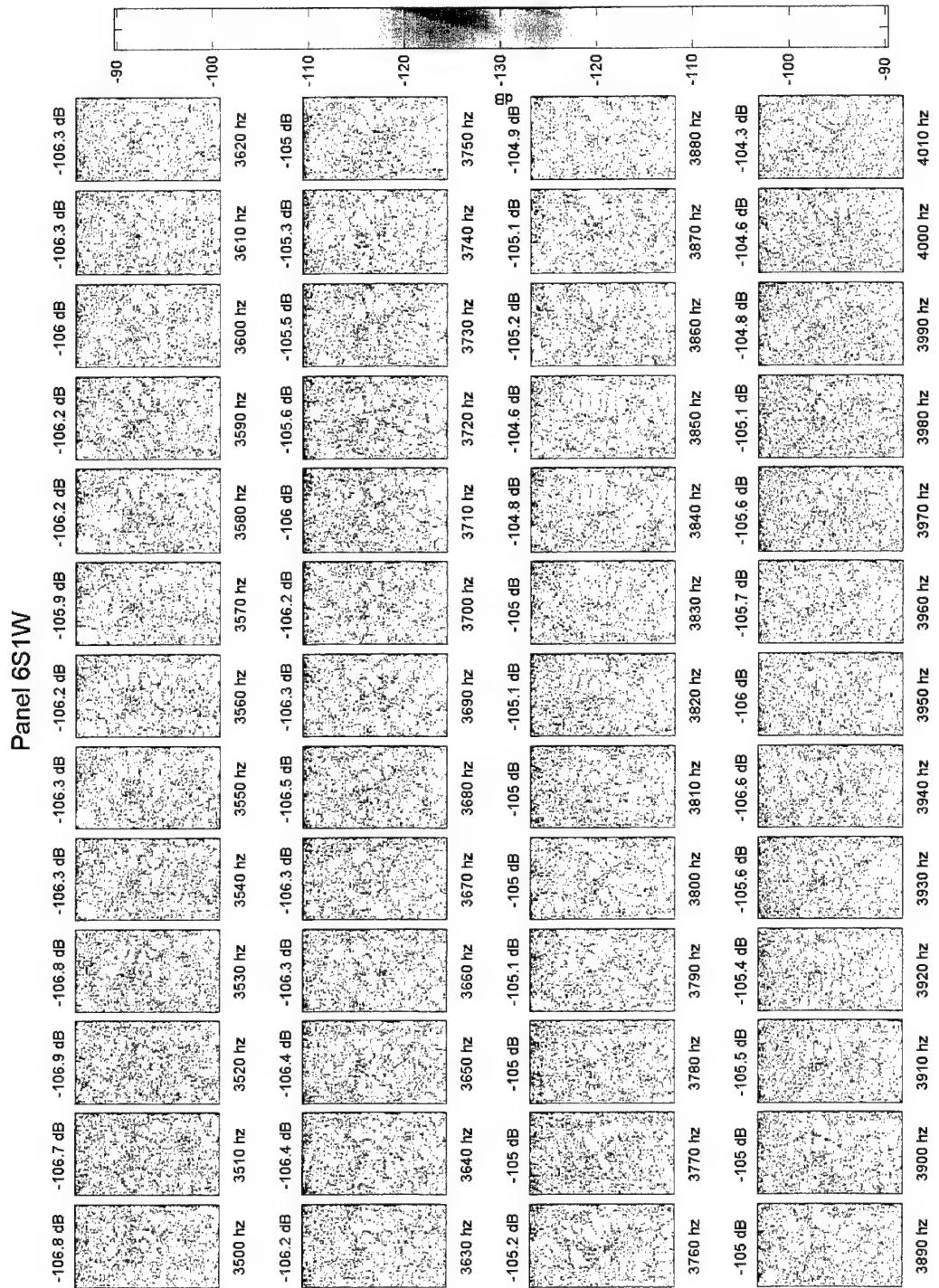


**Figure 6f**



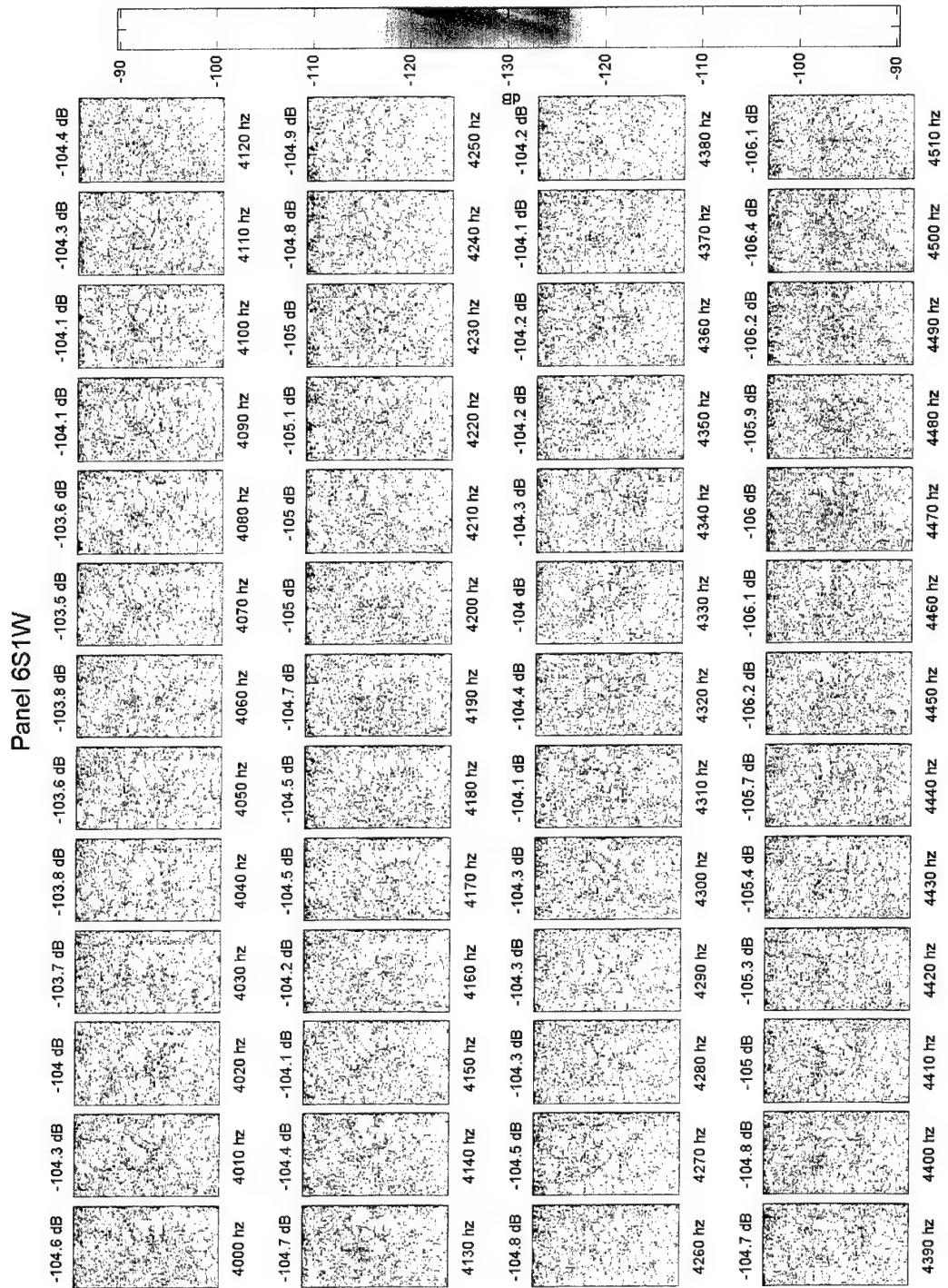
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**Figure 6g**



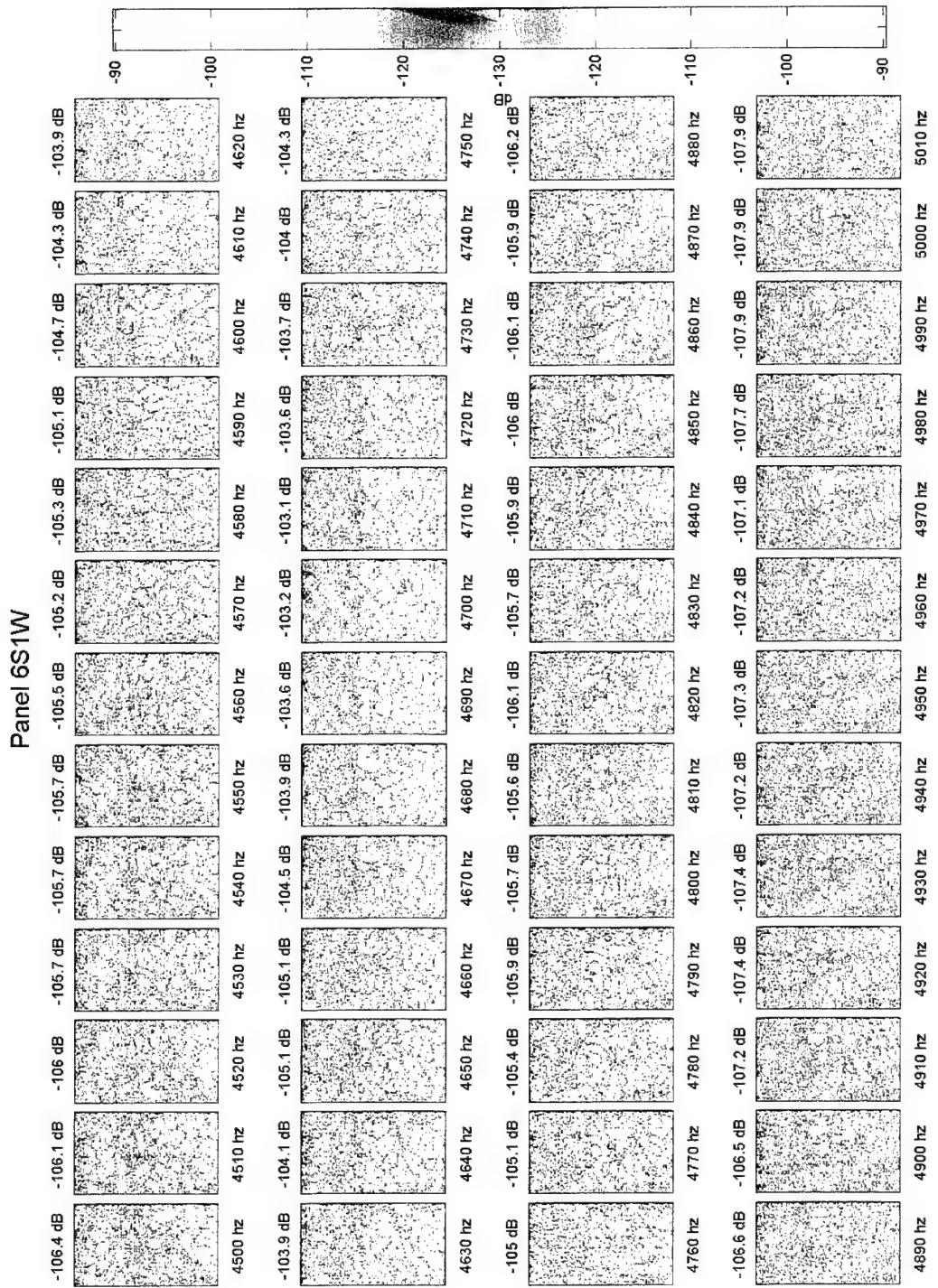
**Figure 6h**

Single Surface Scan file: SCAN\_LAST\_30INV\_LDV\_XFN plotted: 22-Jan-2003 vignola



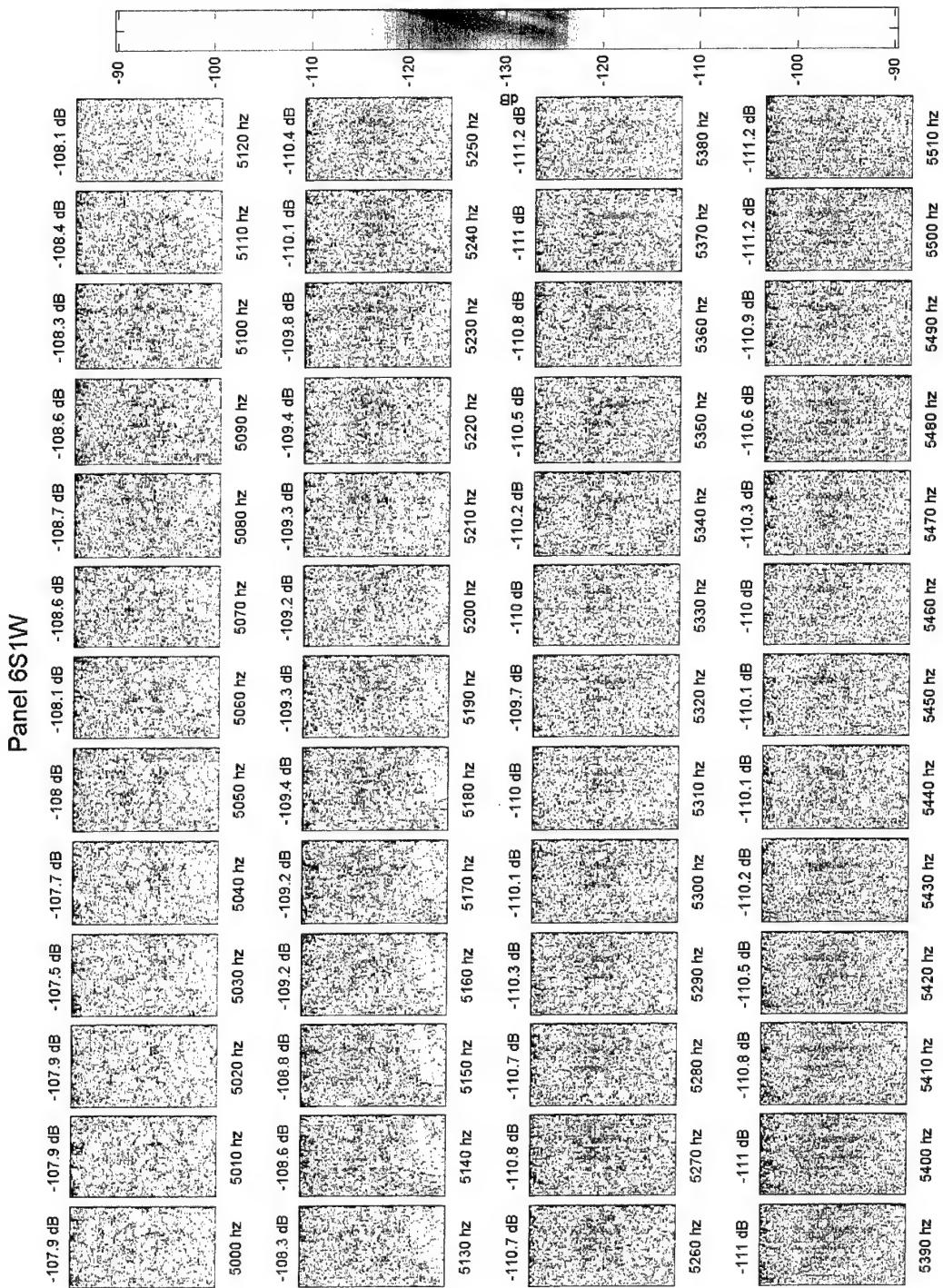
Single Surface Scan file: SCAN\_LAST\_3UNV\_LDV\_XFN plotted: 22-Jan-2003 vignola

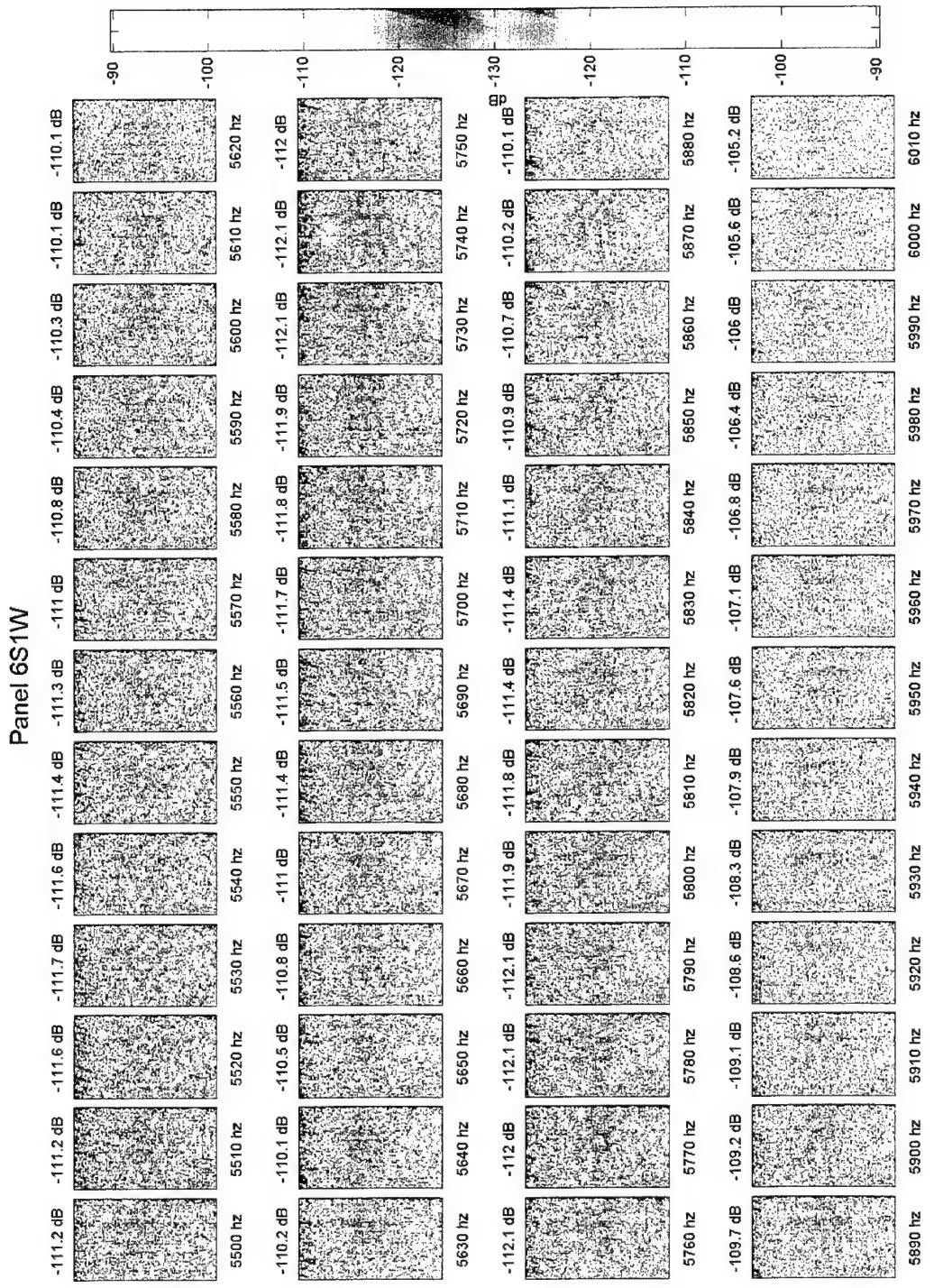
**Figure 6i**



Single Surface Scan file: SCAN\_LAST\_3JUNV\_LDV.XFN plotted: 22-Jan-2003 vignola

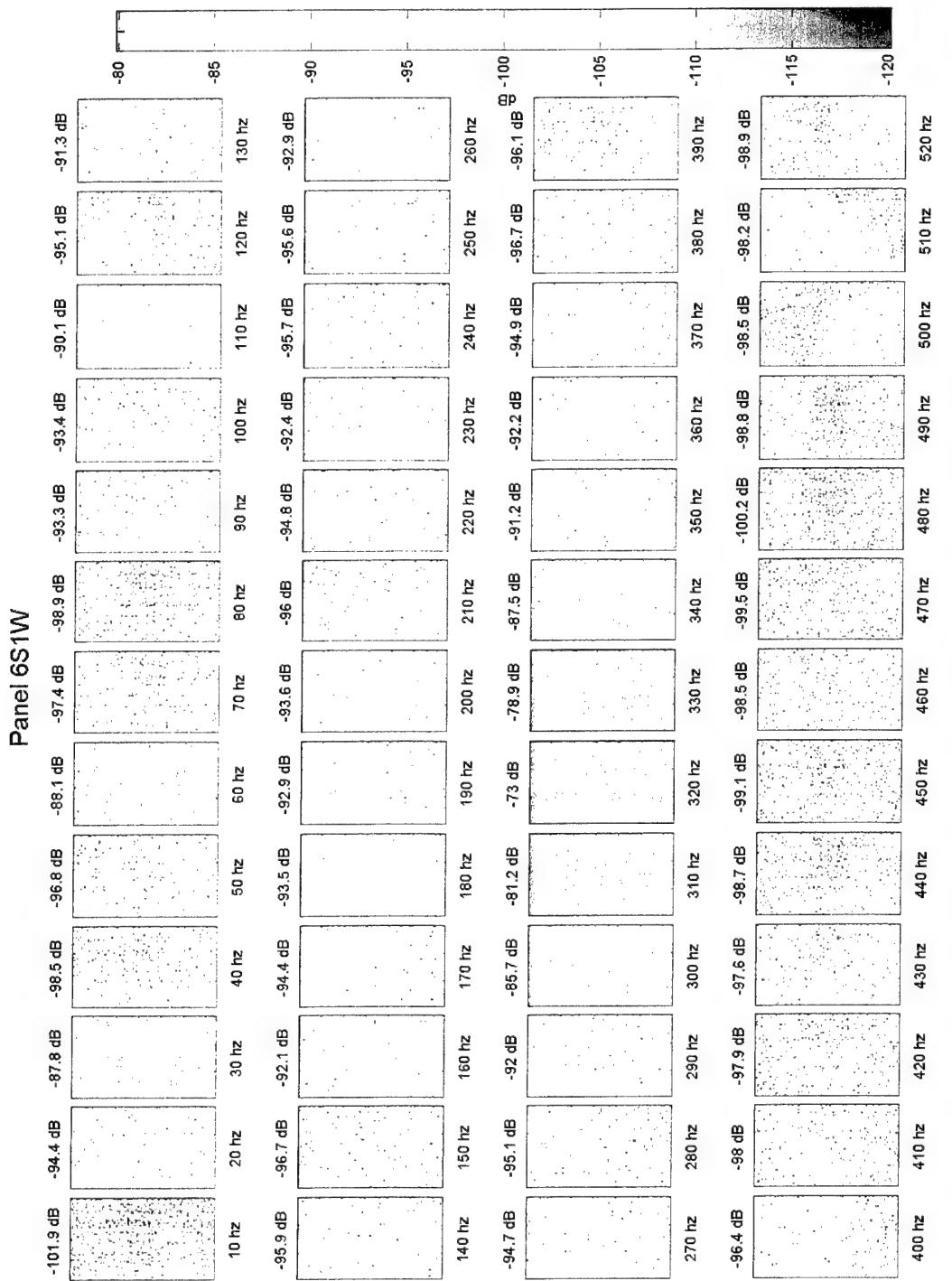
**Figure 6j**



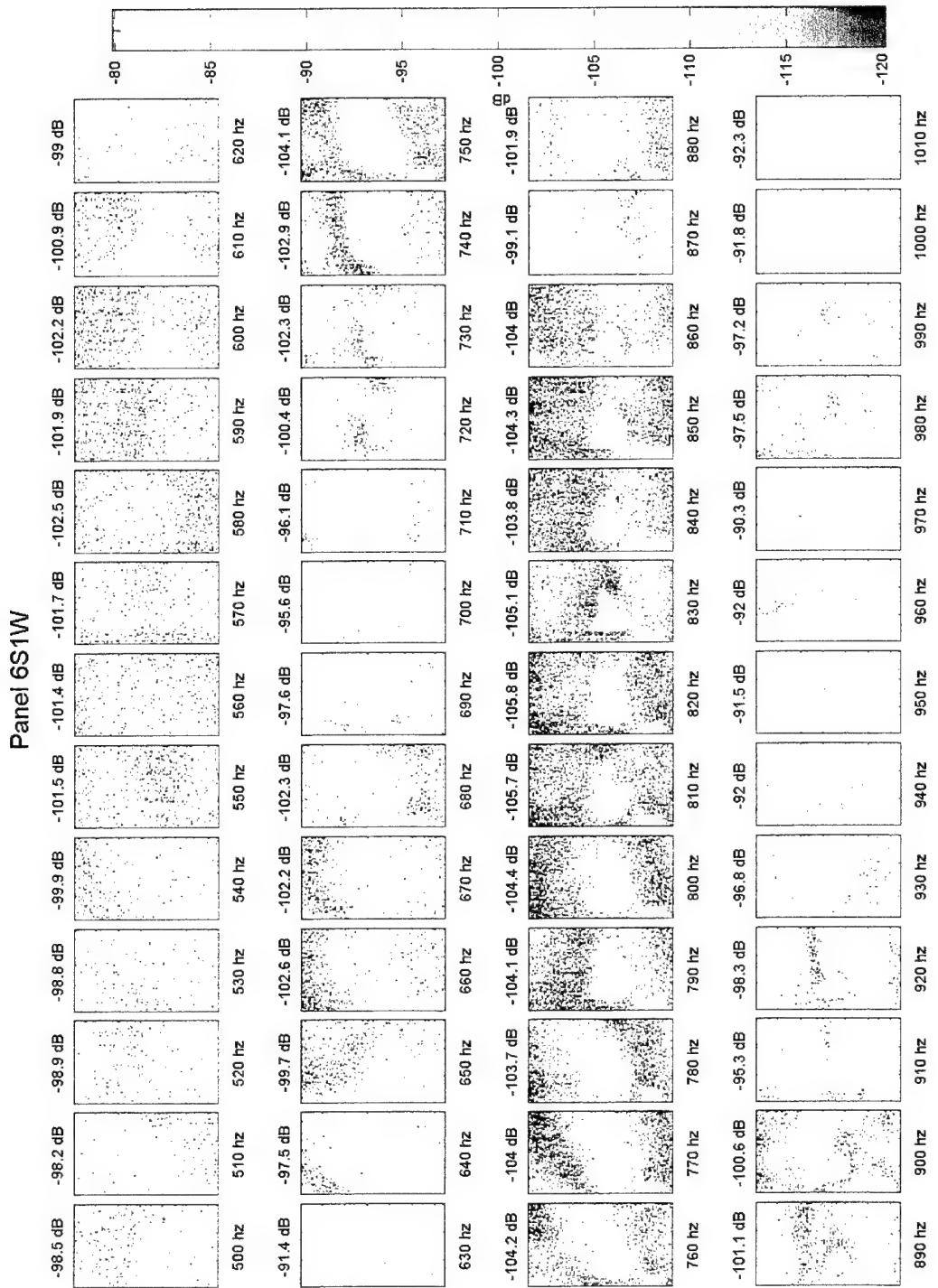


Single Surface Scan file: SCAN\_LAST\_3JUNV\_LDV\_XFN plotted: 22-Jan-2003 vignola

Figure 6|

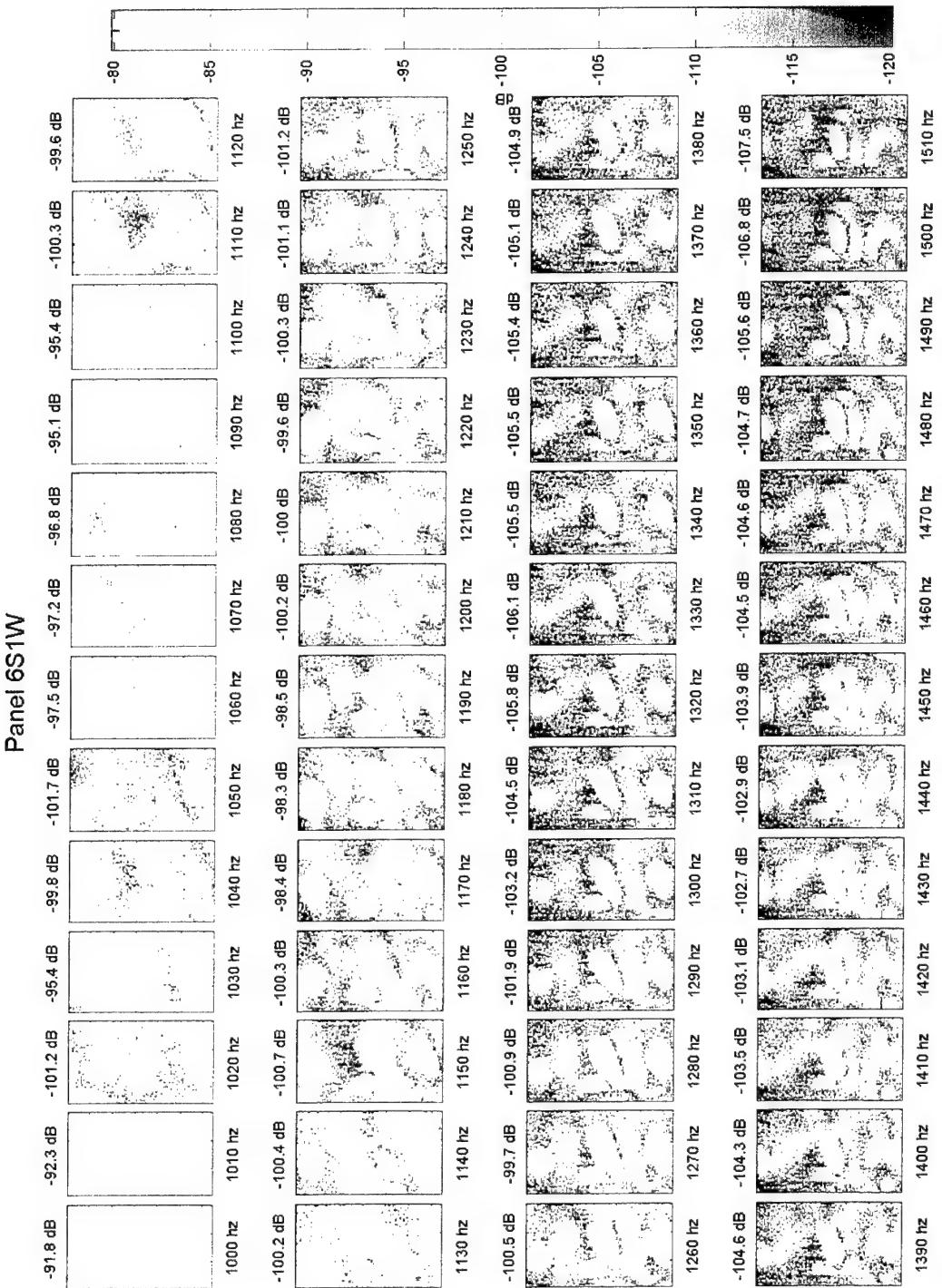


**Figure 6m**



Single Surface Scan file: SCAN\_LAST\_3JUNV\_LDV\_XFN plotted: 22-Jan-2003 vignola

**Figure 6n**



**Figure 6o**

Single Surface Scan file: SCAN\_LAST\_3UVN\_LDV.XFN plotted: 22-Jan-2003 vignola

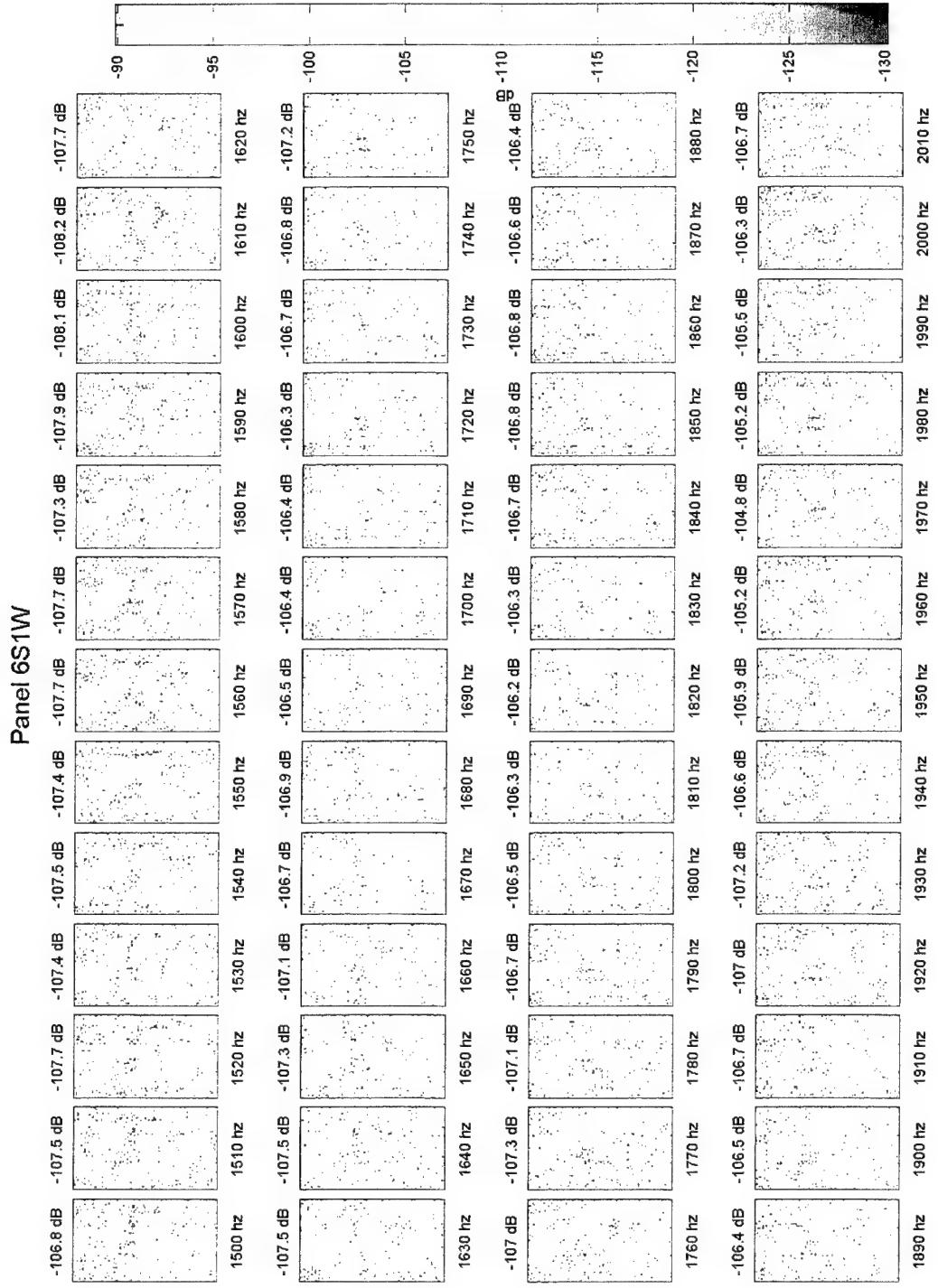
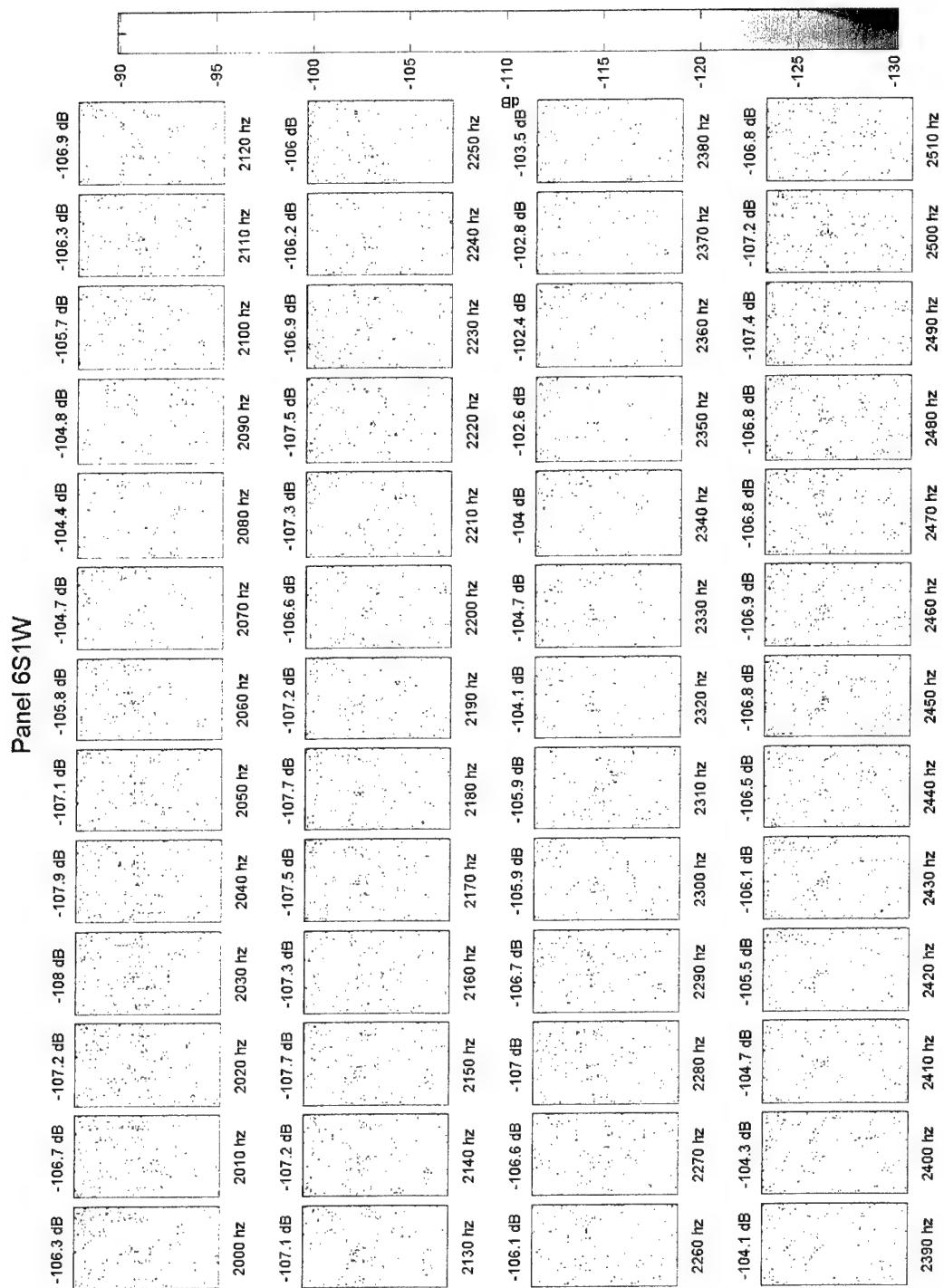


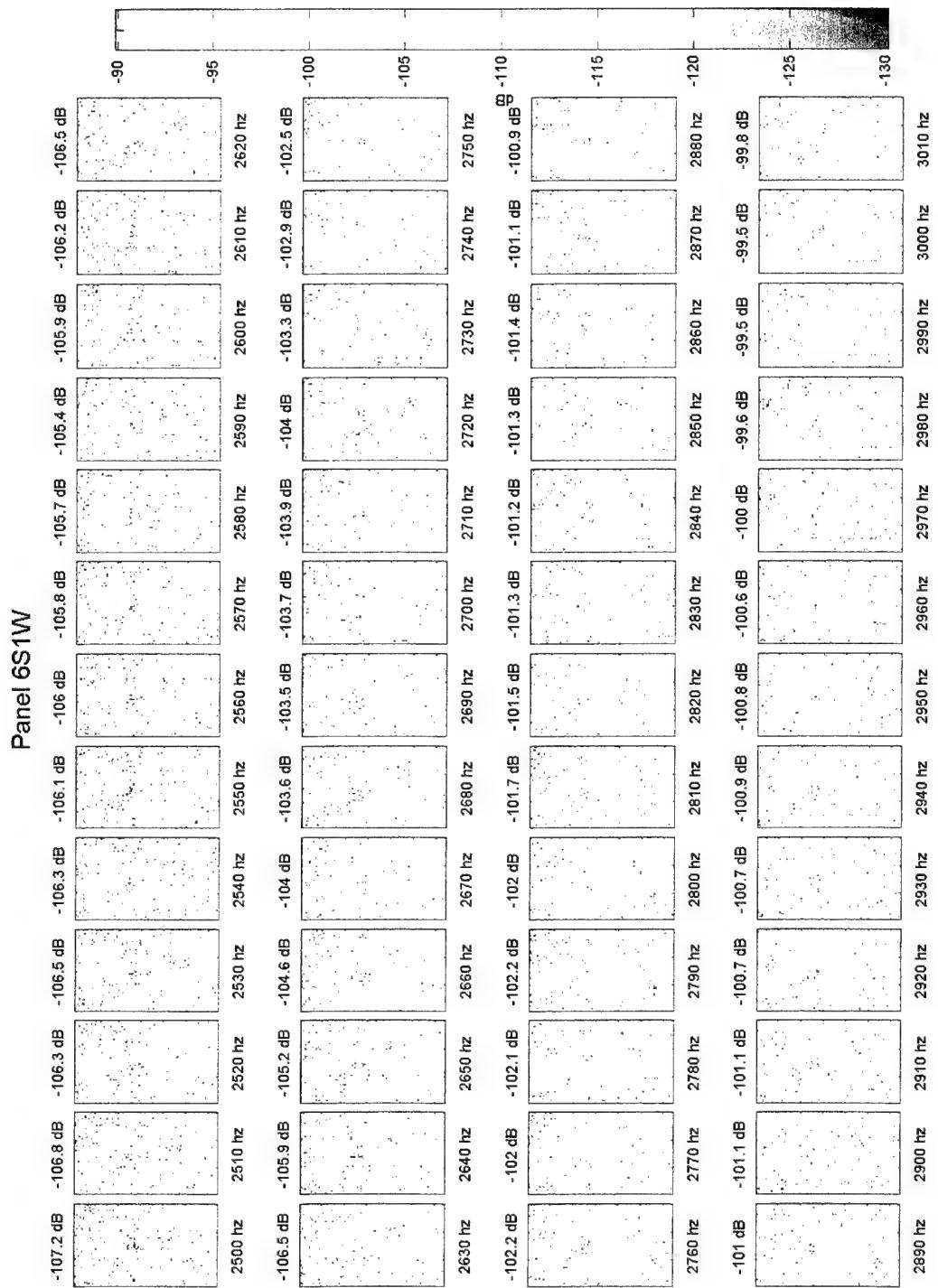
Figure 6p

Single Surface Scan file: SCAN\_LAST\_3UNV\_LDV.XFN plotted: 22-Jan-2003 vignola



**Figure 6q**

Single Surface Scan file: SCAN\_LAST\_3UNV\_LDV/XFN plotted: 22-Jan-2003 vignola

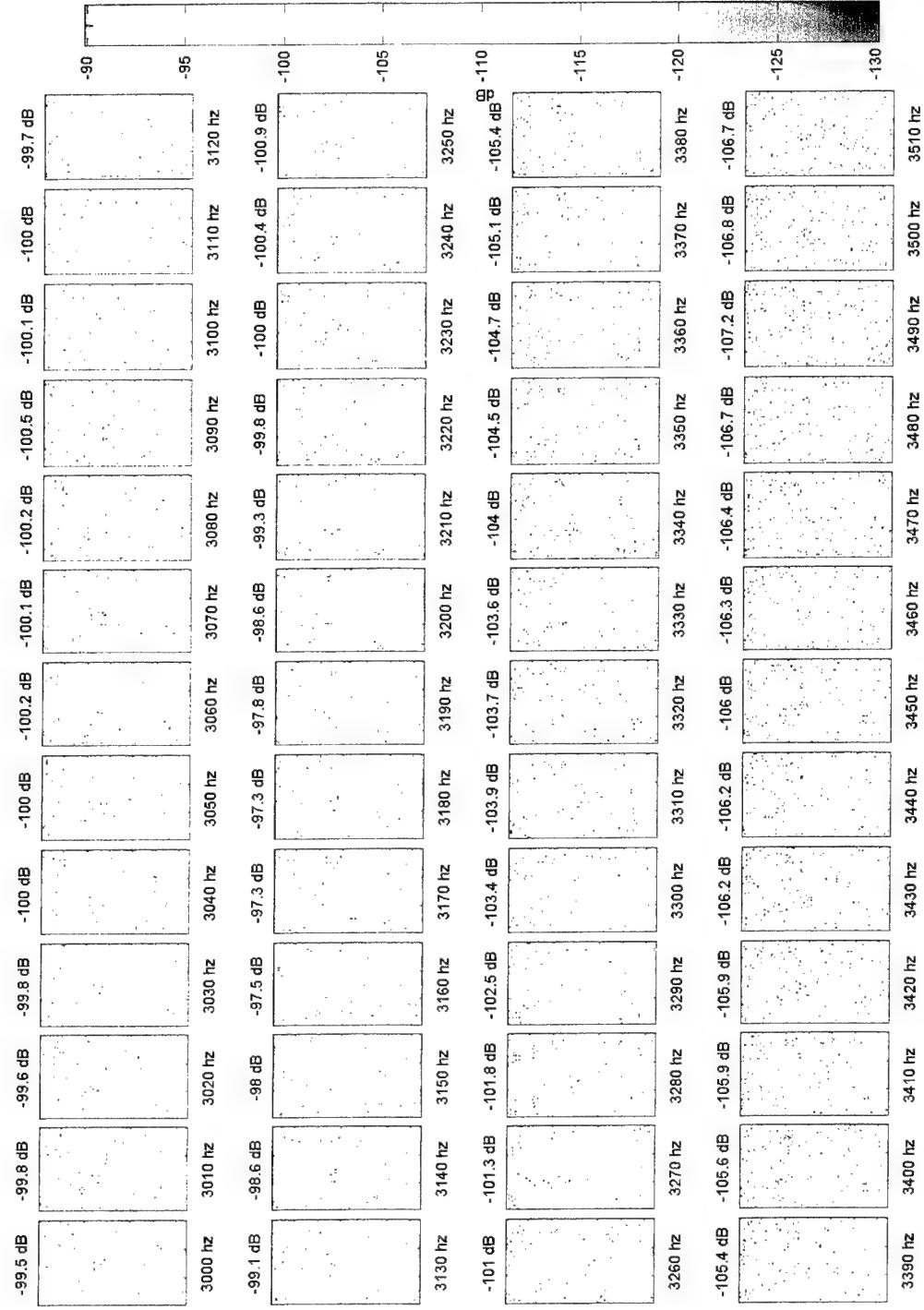


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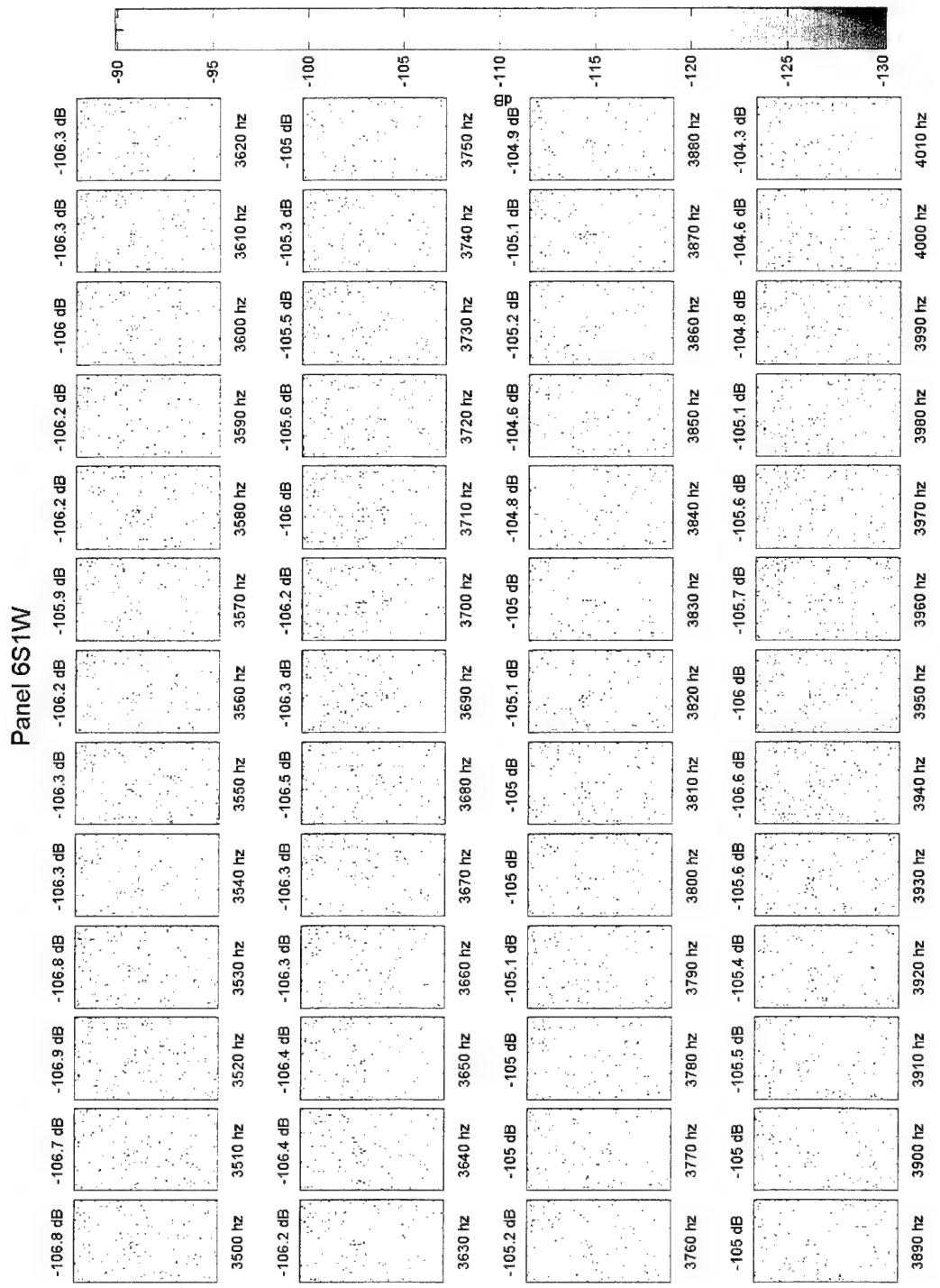
Figure 6r

Panel 6S1W



Single Surface Scan file: SCAN\_LAST\_3UNV\_LDV\_XFN plotted: 22-Jan-2003 vignola

Figure 6s



Single Surface Scan file: SCAN\_LAST\_3UNV\_LDV\_XFN plotted: 22-Jan-2003 vignola

**Figure 6†**

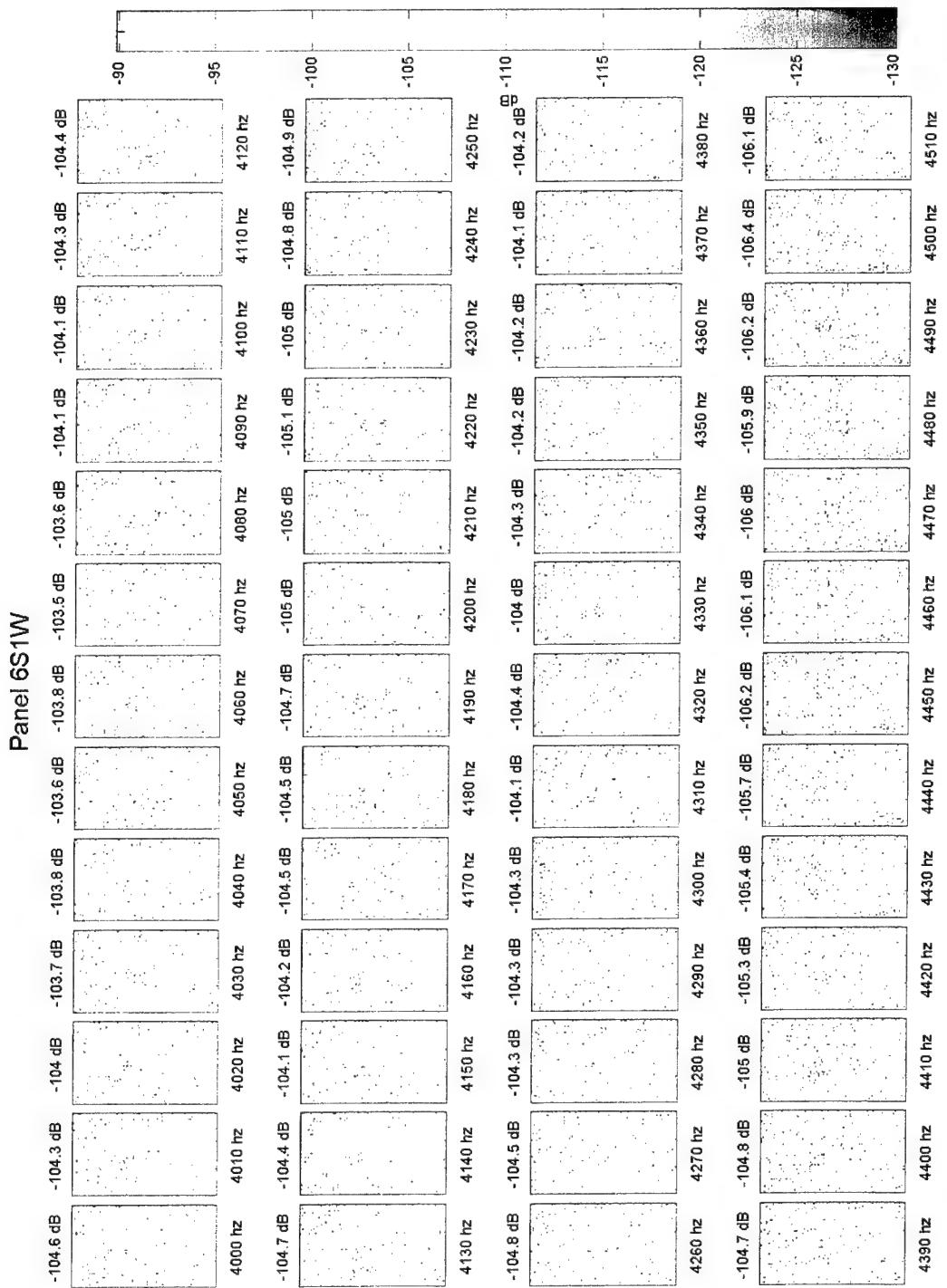


Figure 6u

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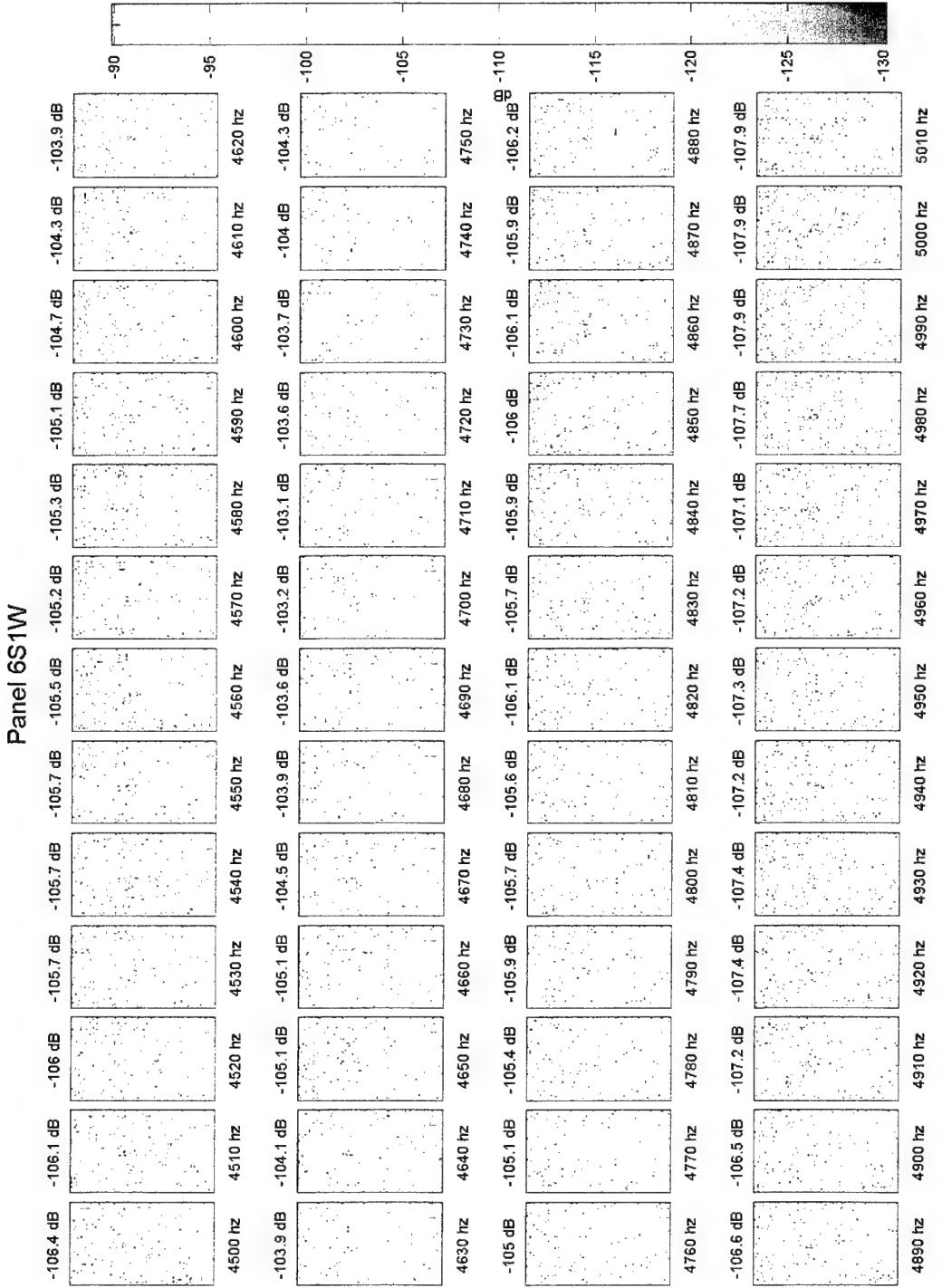
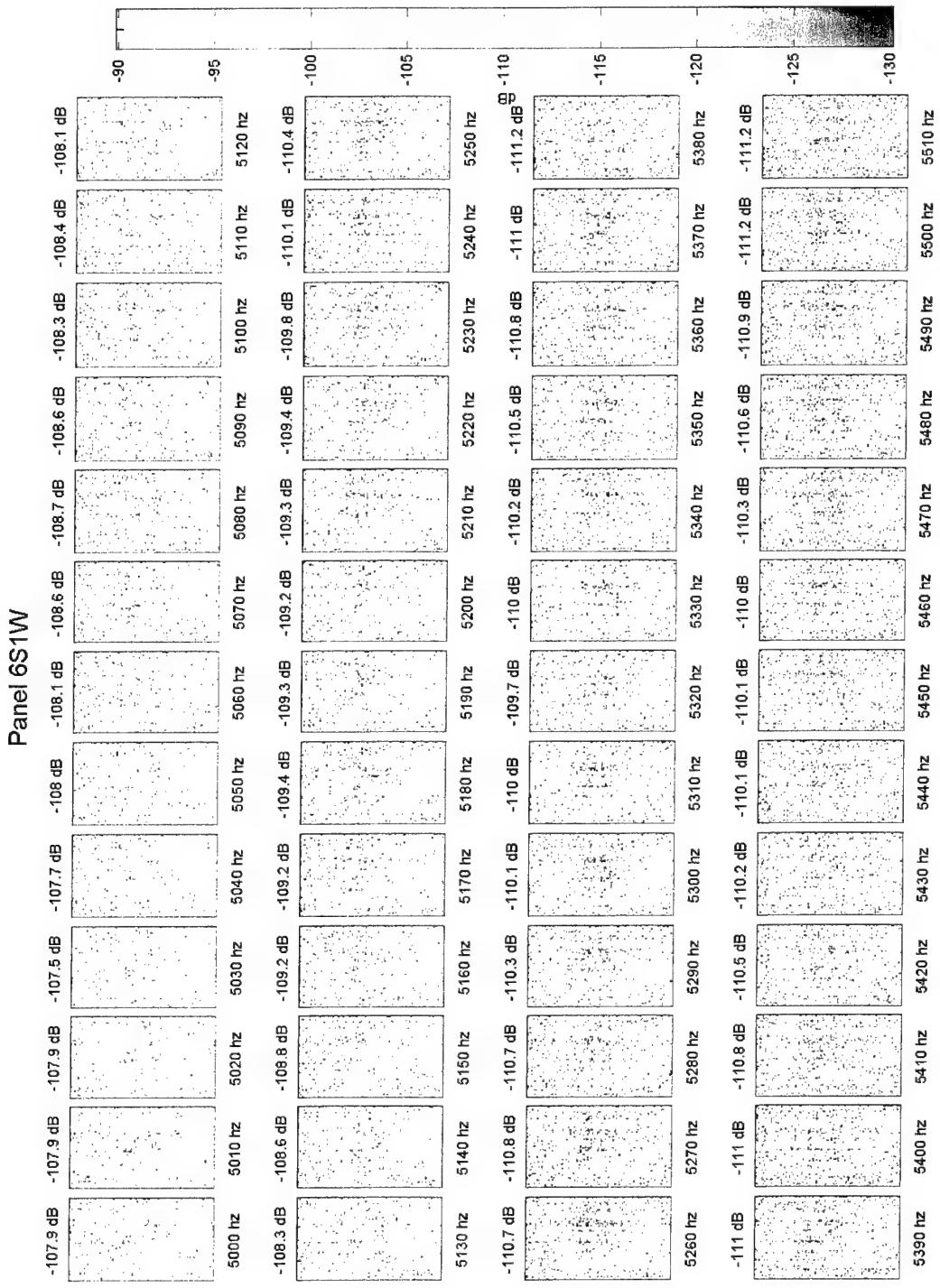


Figure 6v

Single Surface Scan file: SCAN\_LAST\_3UNV\_LDV\_XFN plotted: 22-Jan-2003 vignola



Single Surface Scan file: SCAN\_LAST\_3LINV\_LDV\_XFN plotted: 22-Jan-2003 vignola

Figure 6w

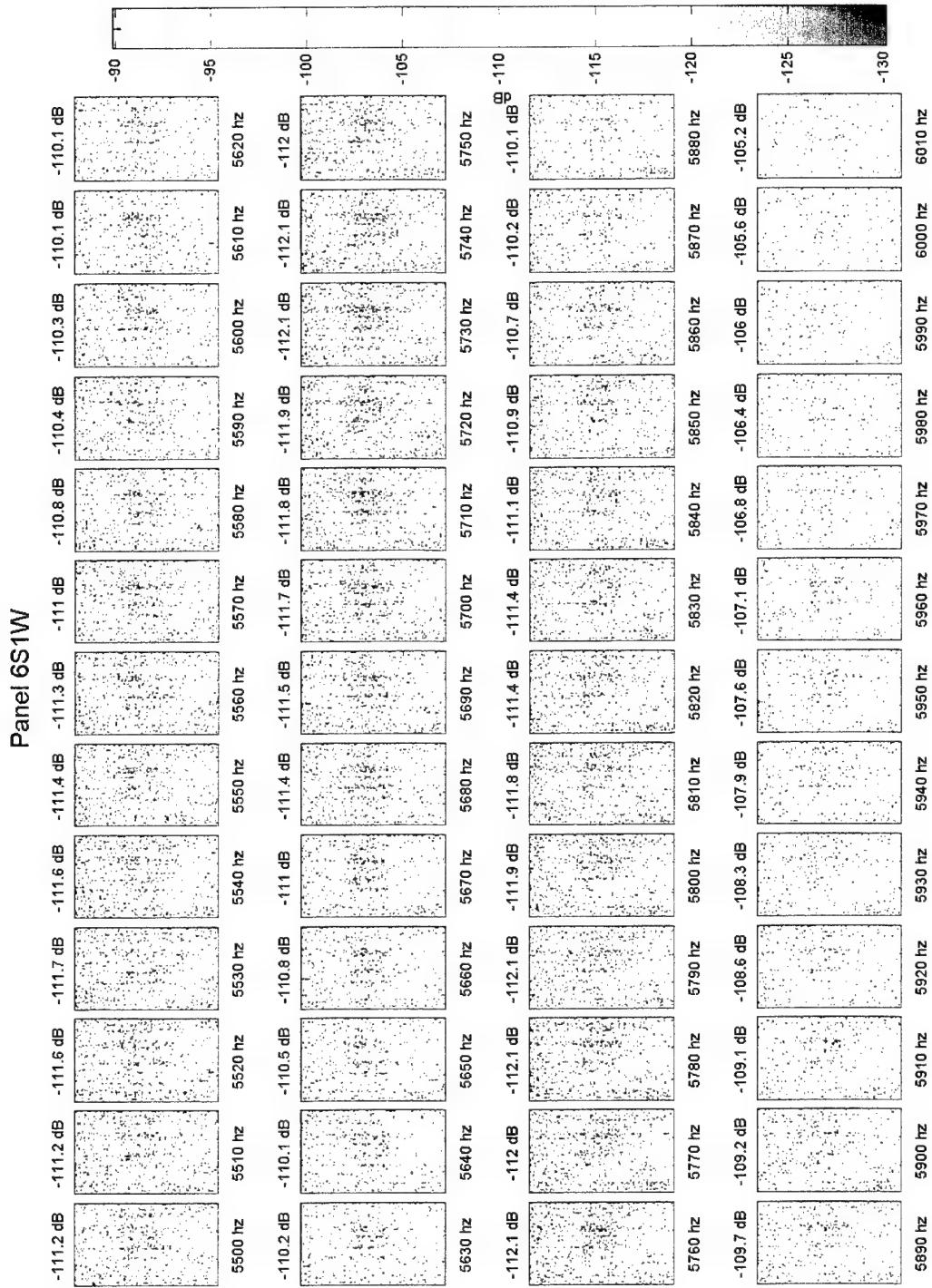


Figure 6x

Single Surface Scan file: SCAN LAST 3UNV LDV XEN Blotted: 22-Jan-2003 Vignola

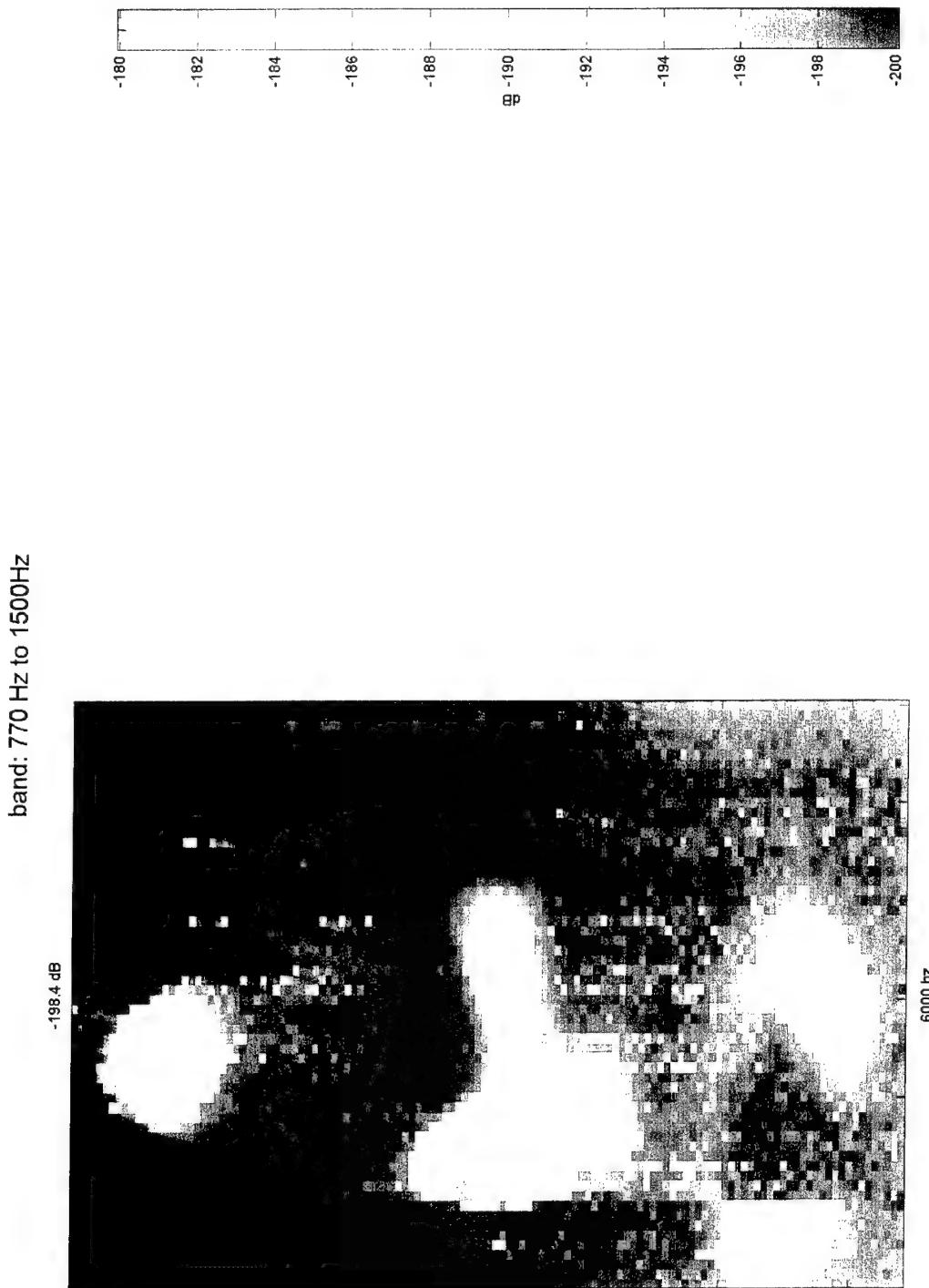


Figure 7a

band: 1090 Hz to 1130Hz



Single Surface Scan file: SCAN\_LAST\_3UNV\_LDV.XFN plotted: 22-Jan-2003 vignola

Figure 7b

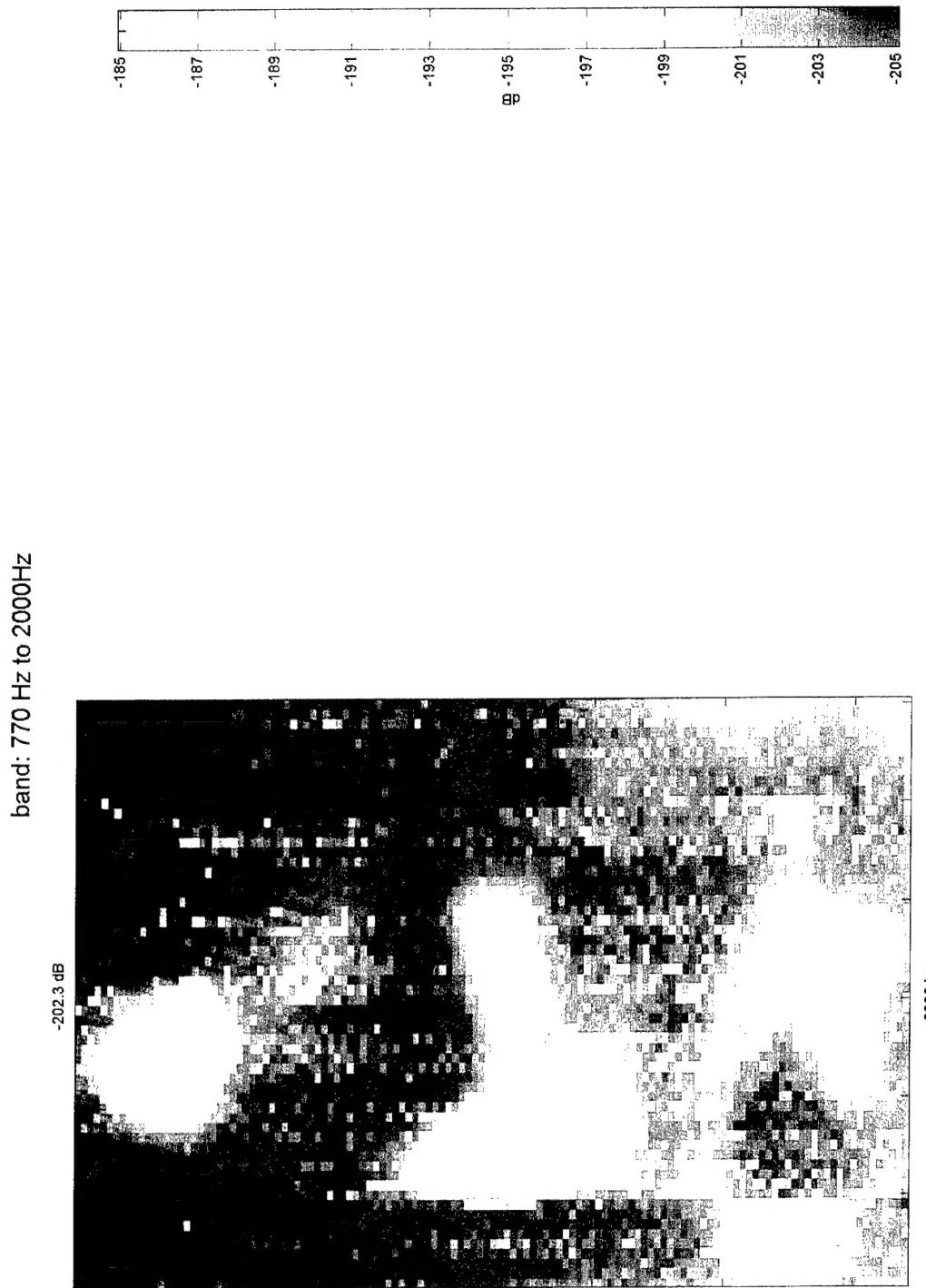


Figure 7c

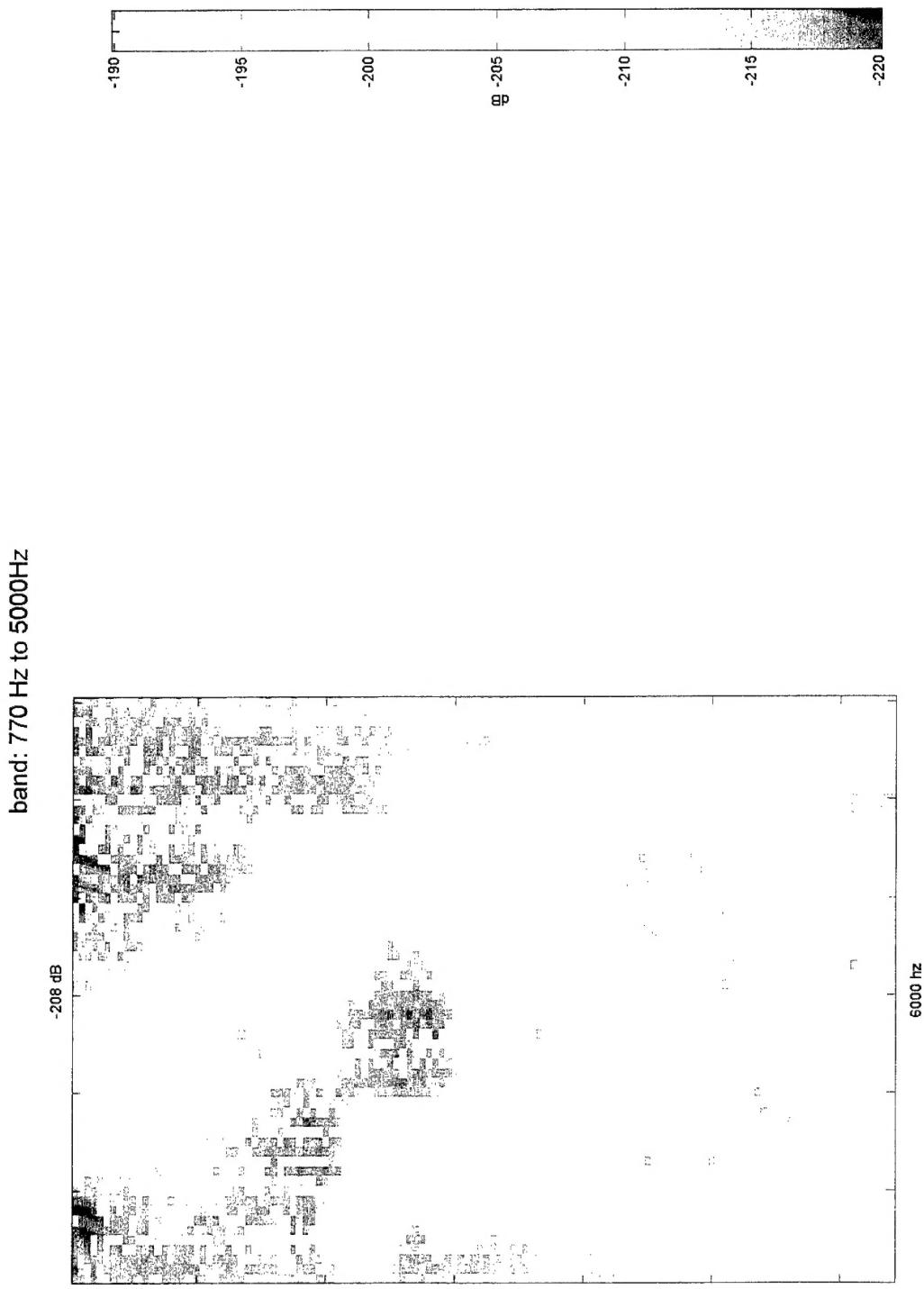


Figure 8

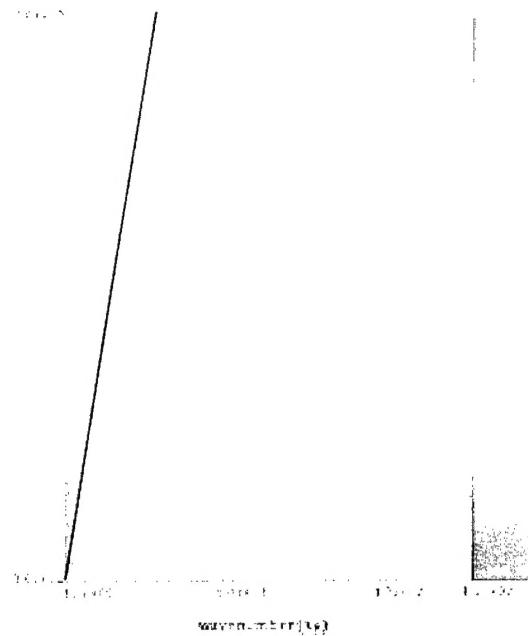


Figure 9 - Dispersion

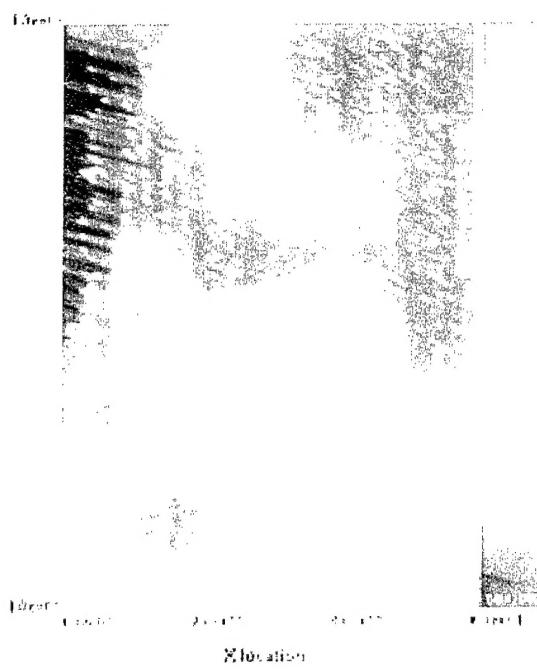


Figure 10 - Cross correlation, 770-1500 Hz

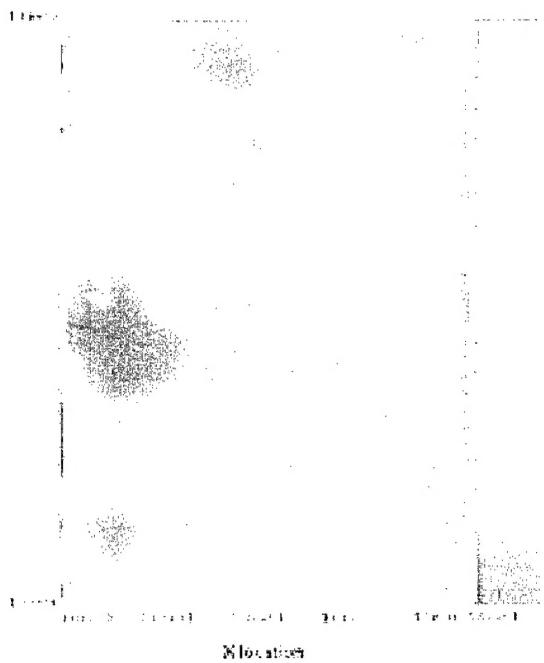


Figure 11 - Shear Wave Velocity<sup>2</sup>, 980 Hz Inversion